Recent PHENIX results on direct photon-hadron correlations

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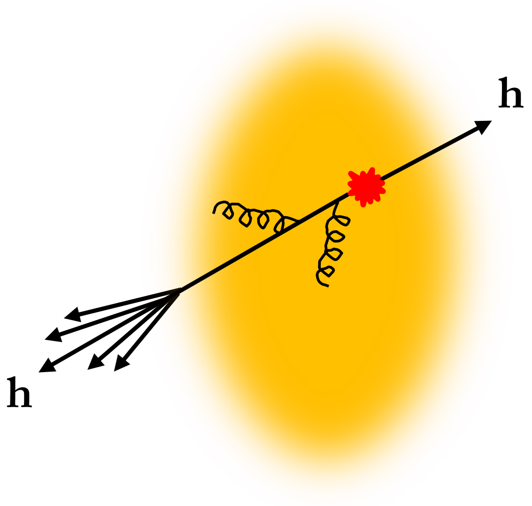
for the PHENIX Collaboration

RHIC & AGS
Annual Users' Meeting
From Protons to Heavy Ions, and Back Again
Hosted By Brookhaven National Laboratory

Study energy loss with hard probes



- High p_T single hadrons
- Dihadron correlations
  - large surface bias
  - relatively easy to measure experimentally
  - poor calibration of the scattered parton energy

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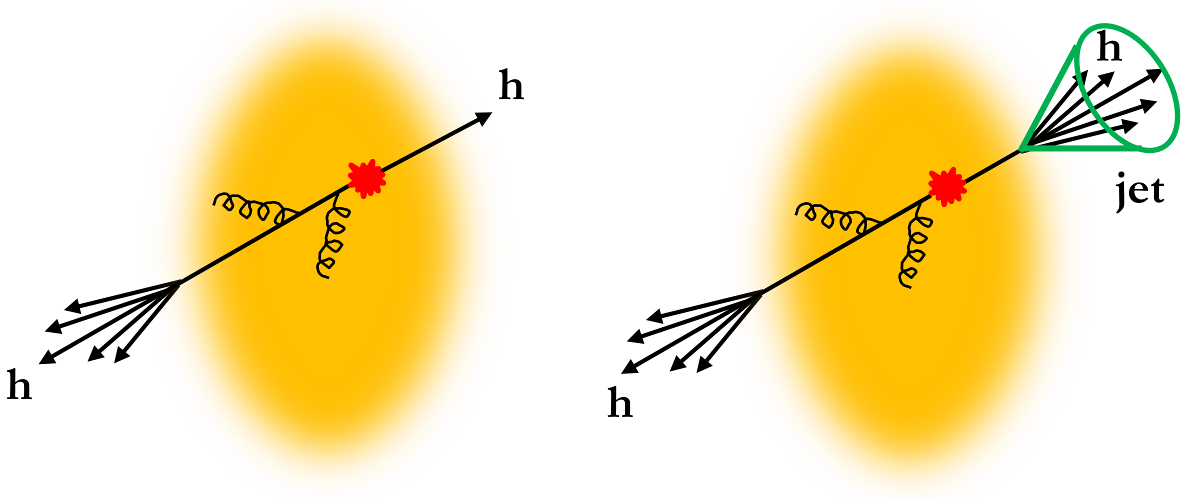

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- Jet-hadron correlations
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  - better measure of the scattered parton energy
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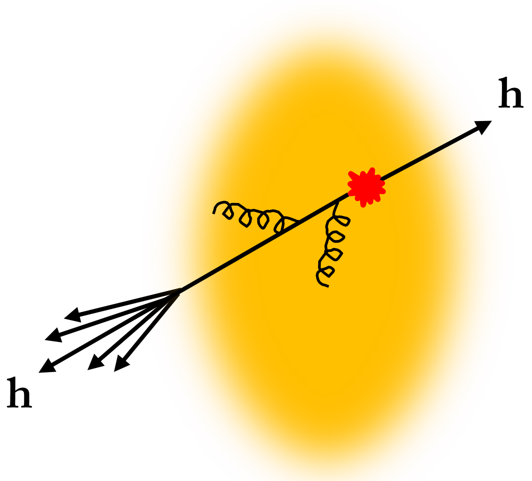

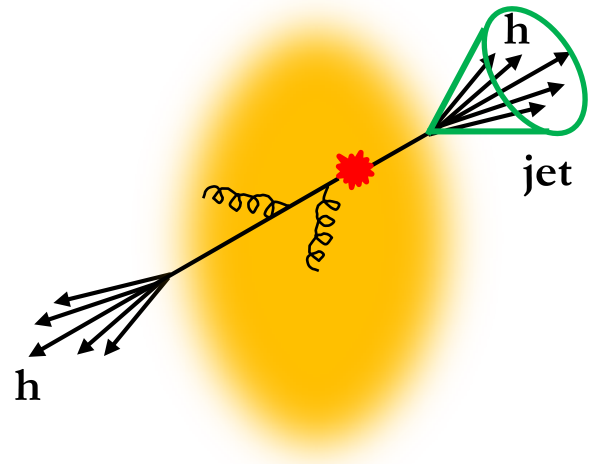

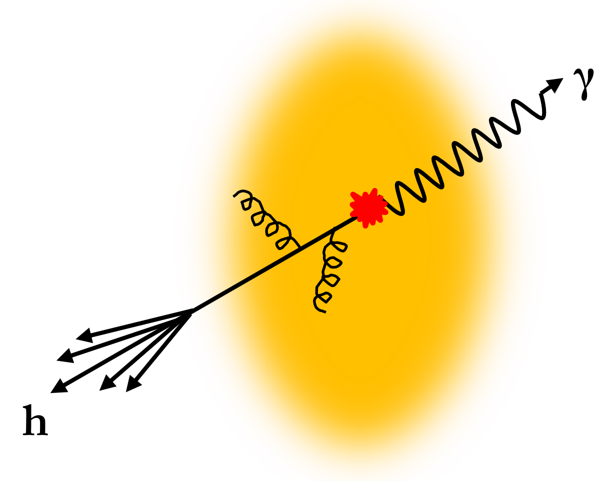

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- Direct photon triggered correlations (γ_{dir}-h, γ_{dir}-jet)

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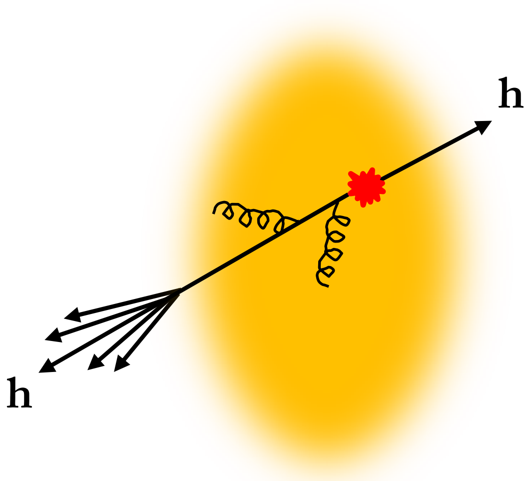

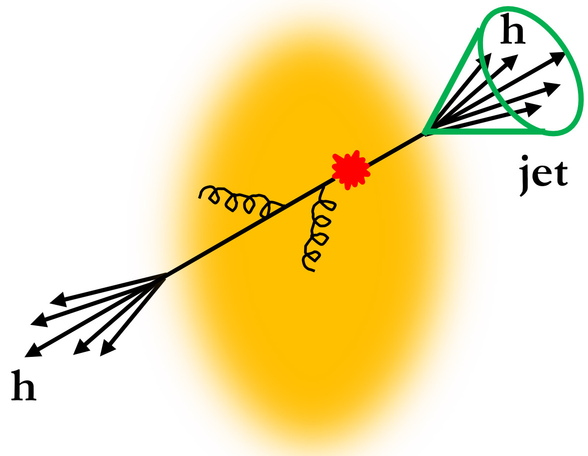

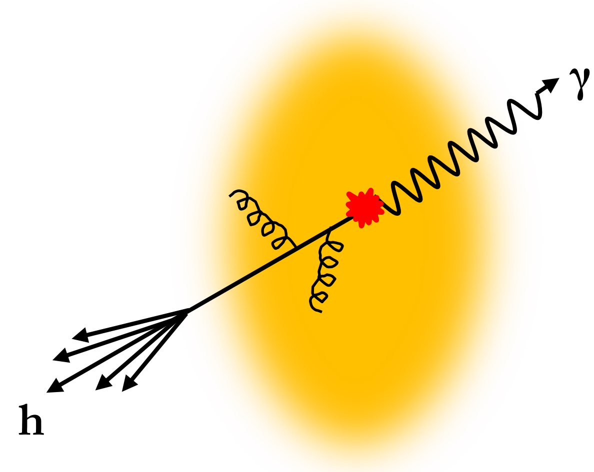

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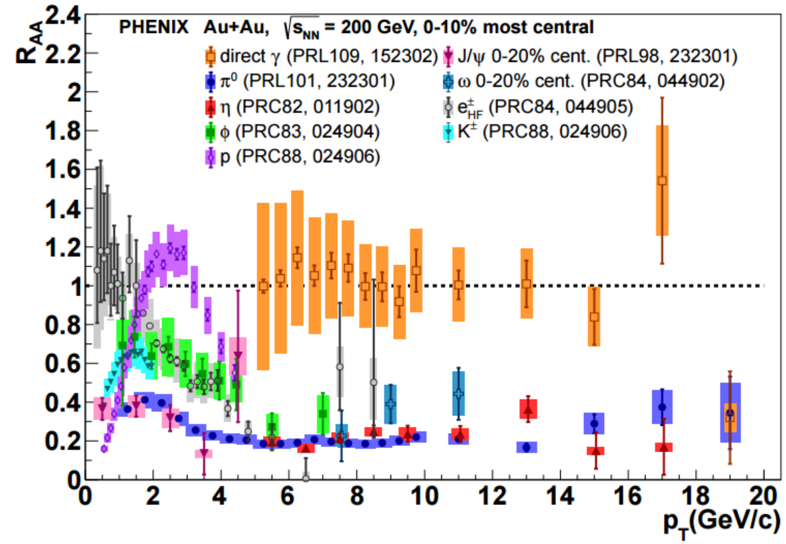
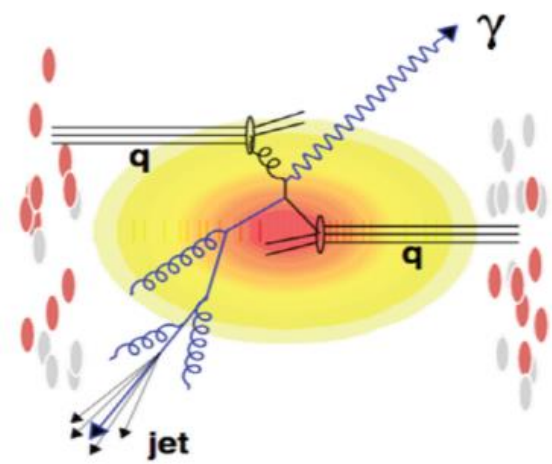
Golden channel

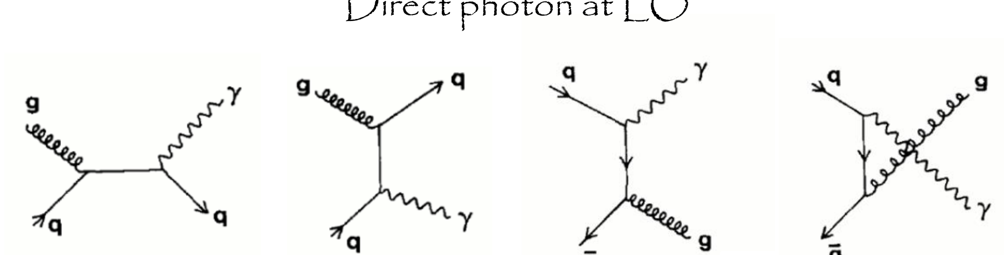
Why γ_{direct}-h?

- Direct photons
  - Do not interact strongly with medium
  - Yield at high p_T dominated by hard processes
- γ_{direct}-h correlation measurement
  - No trigger surface bias
  - Trigger photon p_T - most direct measure of the initial parton energy
  - Important complement to other jet measurement
    - different path length dependence
    - different relative contribution from quark vs gluon jets





Direct photon at LO



compton

annihilation

Why γ_{direct}-h?

- (How) are jets affected by the medium and/or vice versa?
- Where does the lost energy go?
- How do jets fragment?
- Are jets modified in small systems?

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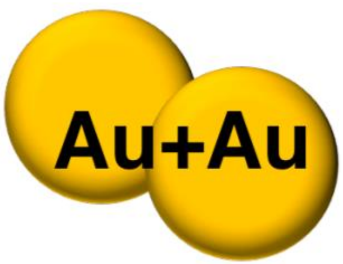
Recent γ-$h^{\pm}$ results in a set of different collision systems measured in PHENIX

Why γ_{direct}-h?

- Directly measure the modification of recoil jet fragmentation function
- Important to understand in-medium energy loss mechanism
- Constrain models in explaining soft particle production



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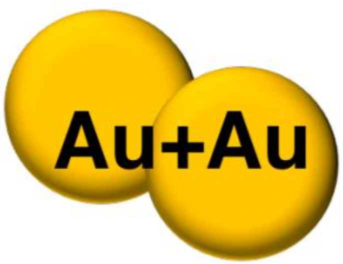

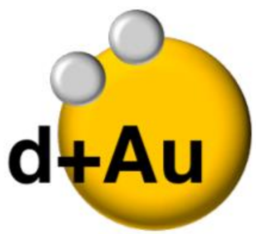

- Probe cold nuclear matter effect
- Test of initial state energy loss hypothesis

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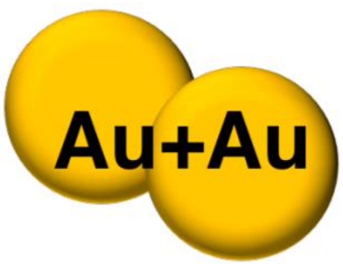
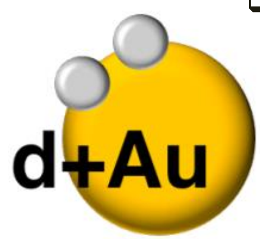
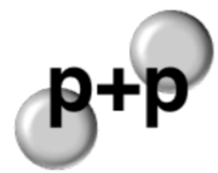




- ❑ Baseline measurement to compare with HI case
- ❑ Test of QCD factorization breaking



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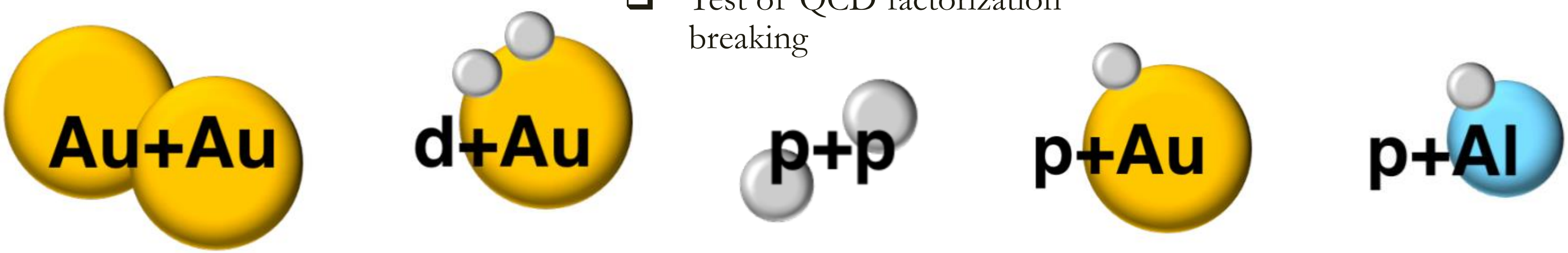

- ❑ Probe cold nuclear matter effect
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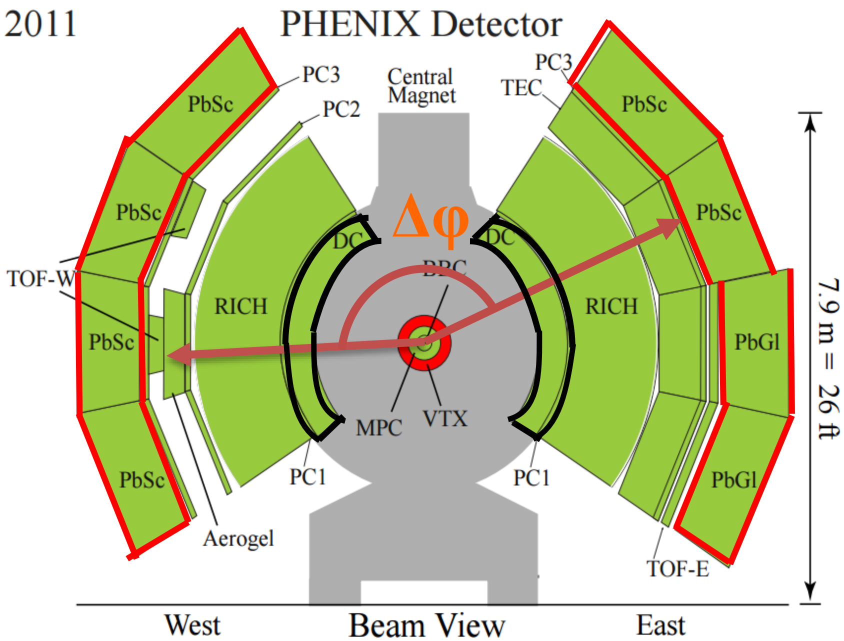
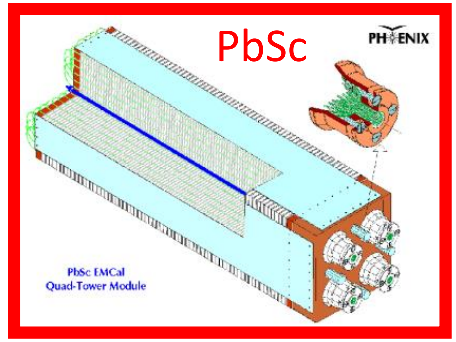
- ❑ Test CNM effect
- ❑ Explore dependence on collision system sizes

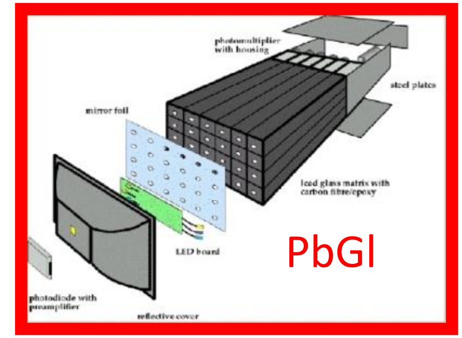
Recent γ-$h^{\pm}$ results in a set of different collision systems measured in PHENIX

Measure γ_{dir}-h in PHENIX: Experimental Setup



Electromagnetic Calorimeters

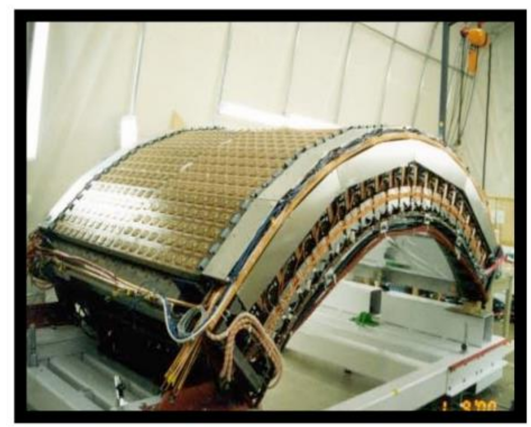




$$\frac{\sigma_{PbSc}(E)}{E} = \frac{8.1\%}{\sqrt{E}} \oplus 2.1\%$$

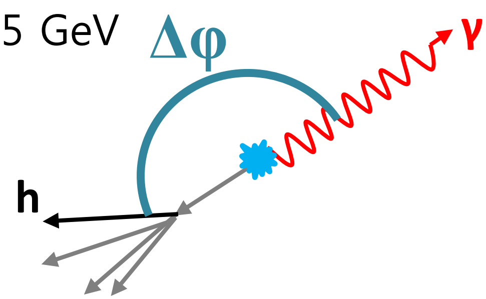
$$\frac{\sigma_{PbGl}(E)}{E} = \frac{5.9\%}{\sqrt{E}} \oplus 0.8\%$$

Drift Chamber



Single wire resolution: 165 μm

- ❑ Central arm acceptance: $|\eta| < 0.35$, $\Delta\varphi$ – 2 x 90˚
- ❑ **Electromagnetic Calorimeter**: measure photons and π^0, merging effect minimal up to ~15 GeV
- ❑ **Drift and Pad Chambers**: measure $h^{\pm}$.
- ❑ Beam-Beam counters:
  - Determine collision centrality/vertex position
  - Minimum bias trigger

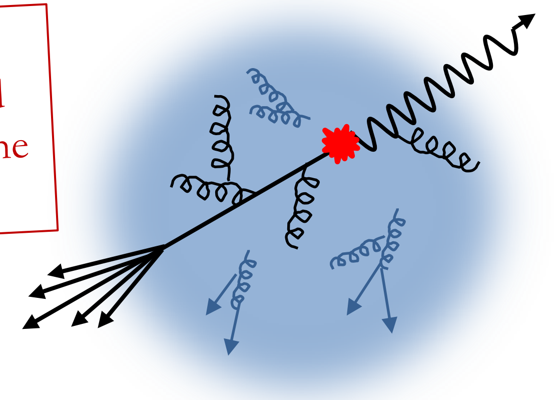


Measure γ_{dir}-h in PHENIX: Extract Jet Signals

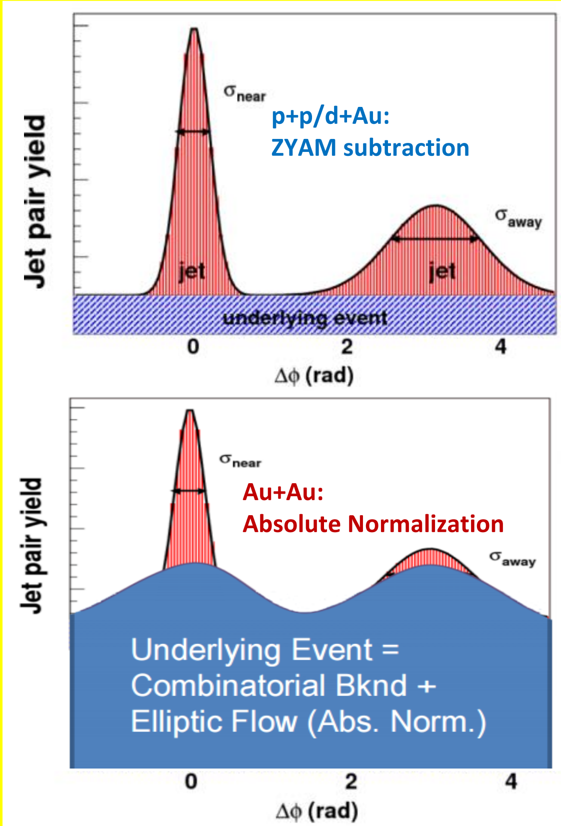
Background sources:

- Particles from two unrelated jets
- One jet-particle and one non-jet particle
- Two non-jet particles

Combinatorial pairs that are not associated with the same jet or the same hard scattering



2-source model



$$\frac{1}{N^{\gamma}_{trig}}\frac{dN^{\gamma-h}}{d\Delta\phi} = Y(\Delta\phi)$$

→ Per-trigger yield

$$Y \propto C(\Delta\phi) - \underset{\text{Norm}}{b}\left(1 + \underbrace{2\langle v_2^{\gamma}\rangle\langle v_2^{h}\rangle}_{\text{Bkg(Flow)}}\cos 2\Delta\phi\right)$$

$$C(\Delta\phi) = \frac{dN^{pair}_{real}/d\Delta\phi}{dN^{pair}_{mix}/d\Delta\phi}$$

FG: detector acceptance corrected correlations

Event mixing

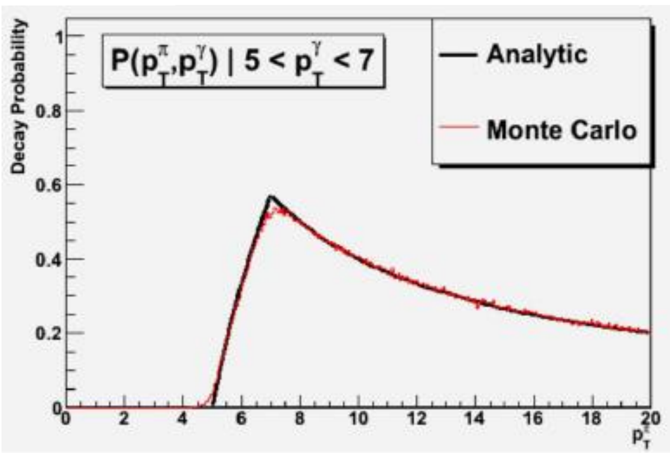
- ✓ Correct for detector acceptance
- ✓ Determine background level

Background pairs are subtracted for both $Y_{inclusive}$ and Y_{decay}

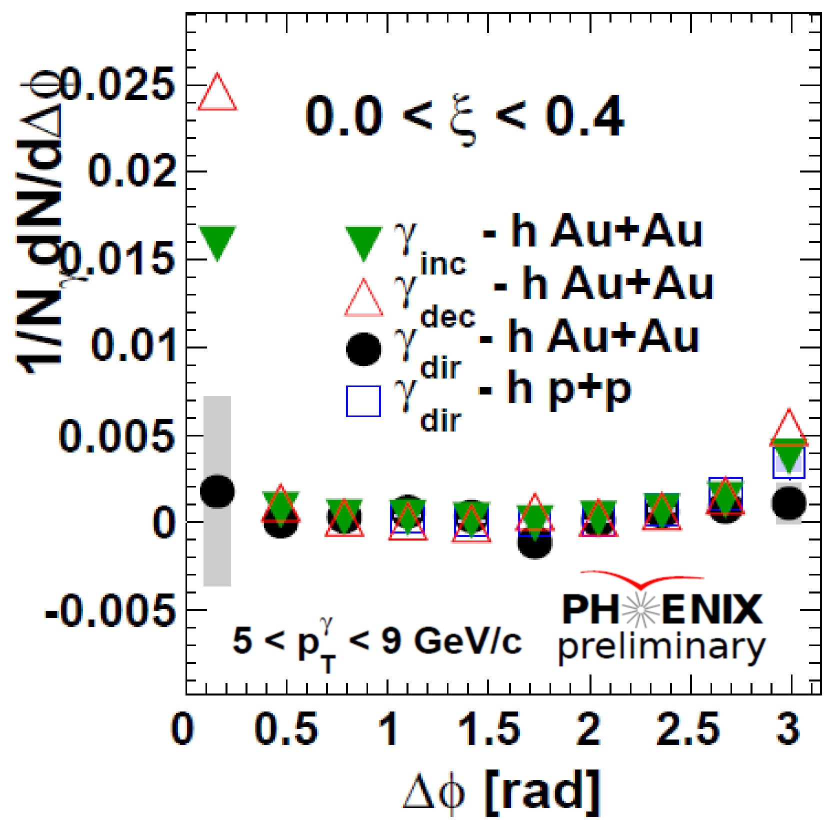
Measure γ_{dir}-h in PHENIX: Extract γ_{dir}-h

Subtract Y_{decay} from $Y_{inclusive}$ to get Y_{direct} using statistical subtraction

$Y_{\pi^0} \rightarrow Y_{decay}$



Direct photon –
any photon that is not from a decay process



Statistical subtraction

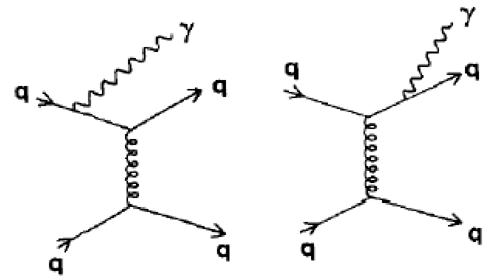
$$Y_{dir} = \frac{R_{\gamma} Y_{inc} - Ydec}{R_{\gamma} - 1}$$

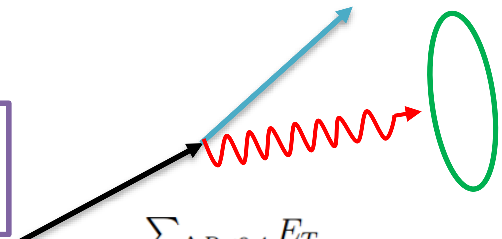
$$R_{\gamma} = N_{inc}/N_{dec}$$

Measure γ_{dir}-h in PHENIX: Extract γ_{dir}-h

- NLO effects $\boxed{p_T^{\gamma} \approx p_T^{jet}?}$
- In p+p, d+Au and p+A collisions, decay photon tagging and an isolation cut is applied event-by-event
  - Improve signal-to-background
  - Reduce non-prompt photons
  - Improve uncertainties
- Remaining decay photons get removed by a statistical subtraction

Photons @ NLO



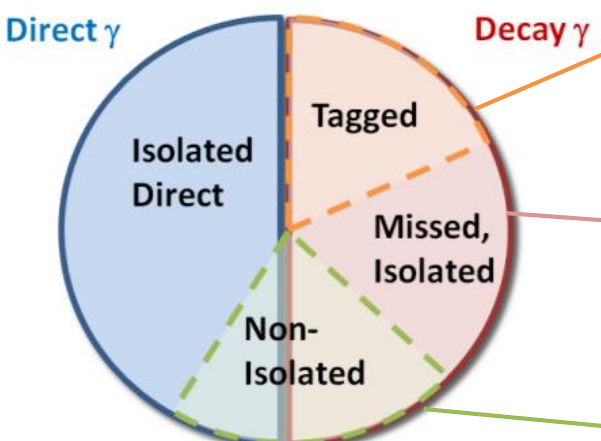


$$Y_{dir}^{iso} = \frac{1}{R_{\gamma}^{eff} - 1} \cdot \left(R_{\gamma}^{eff}\; Y_{inc}^{miss,iso} - Y_{dec}^{miss,iso}\right)$$

$$R_{\gamma}^{eff} \equiv \frac{N_{inc} - N_{decay}^{tag} - N_{inc}^{niso}}{N_{dec}^{miss,iso}}$$

$$\frac{\sum_{\Delta R<0.4} E_T}{E_T^{\gamma}} < 10\%$$

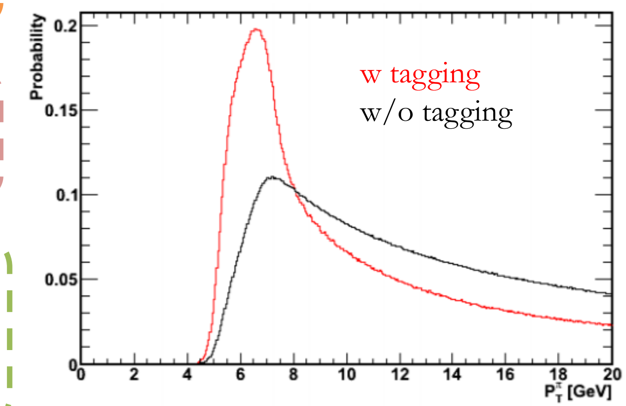
$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$



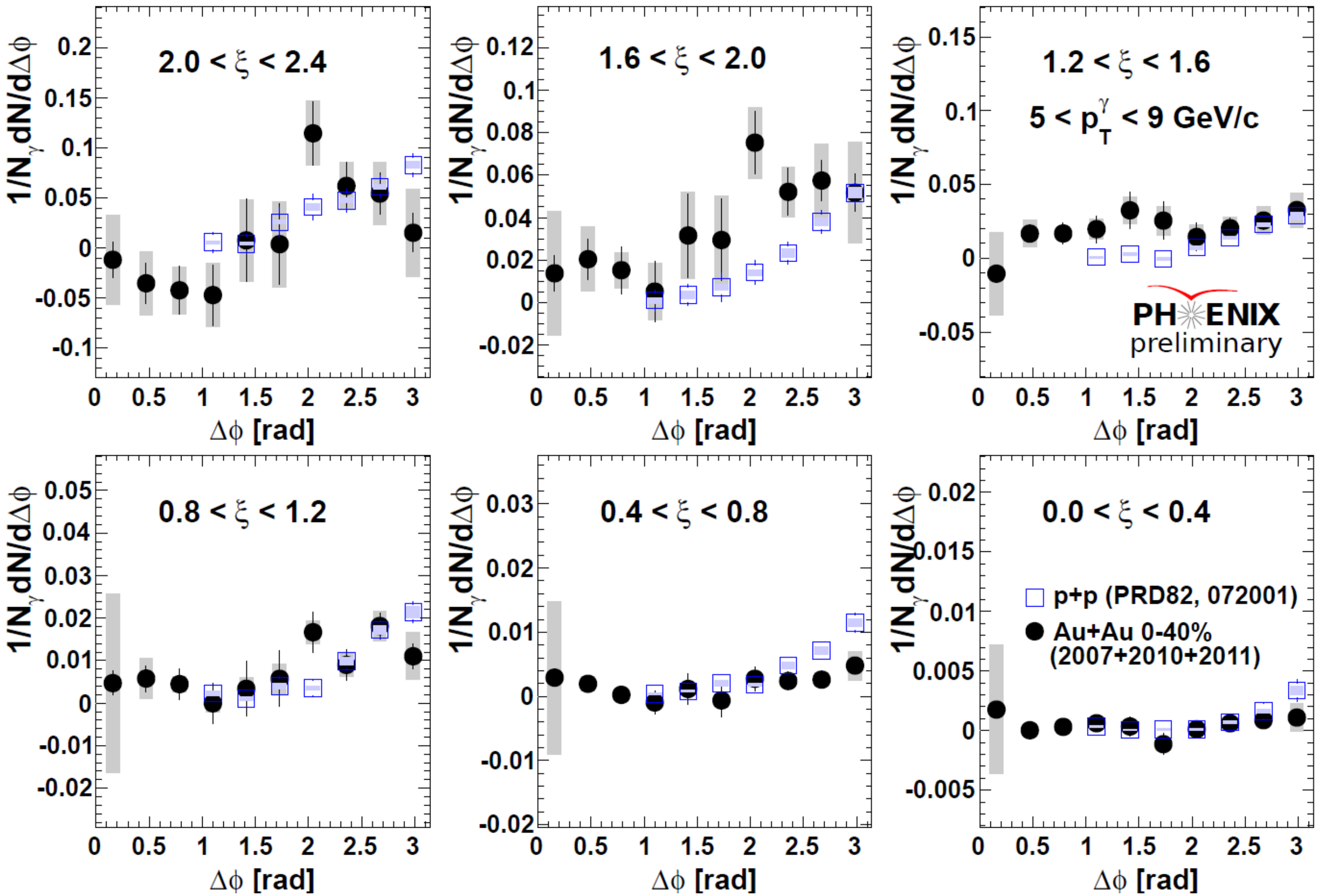
Tagged: decay photons that were tagged as coming from decays

Missed: decay photons that could not be tagged

Non-Isolated: decay or direct photons that were removed by the isolation cut or tagging cut



Measure γ_{dir}-h in Au+Au



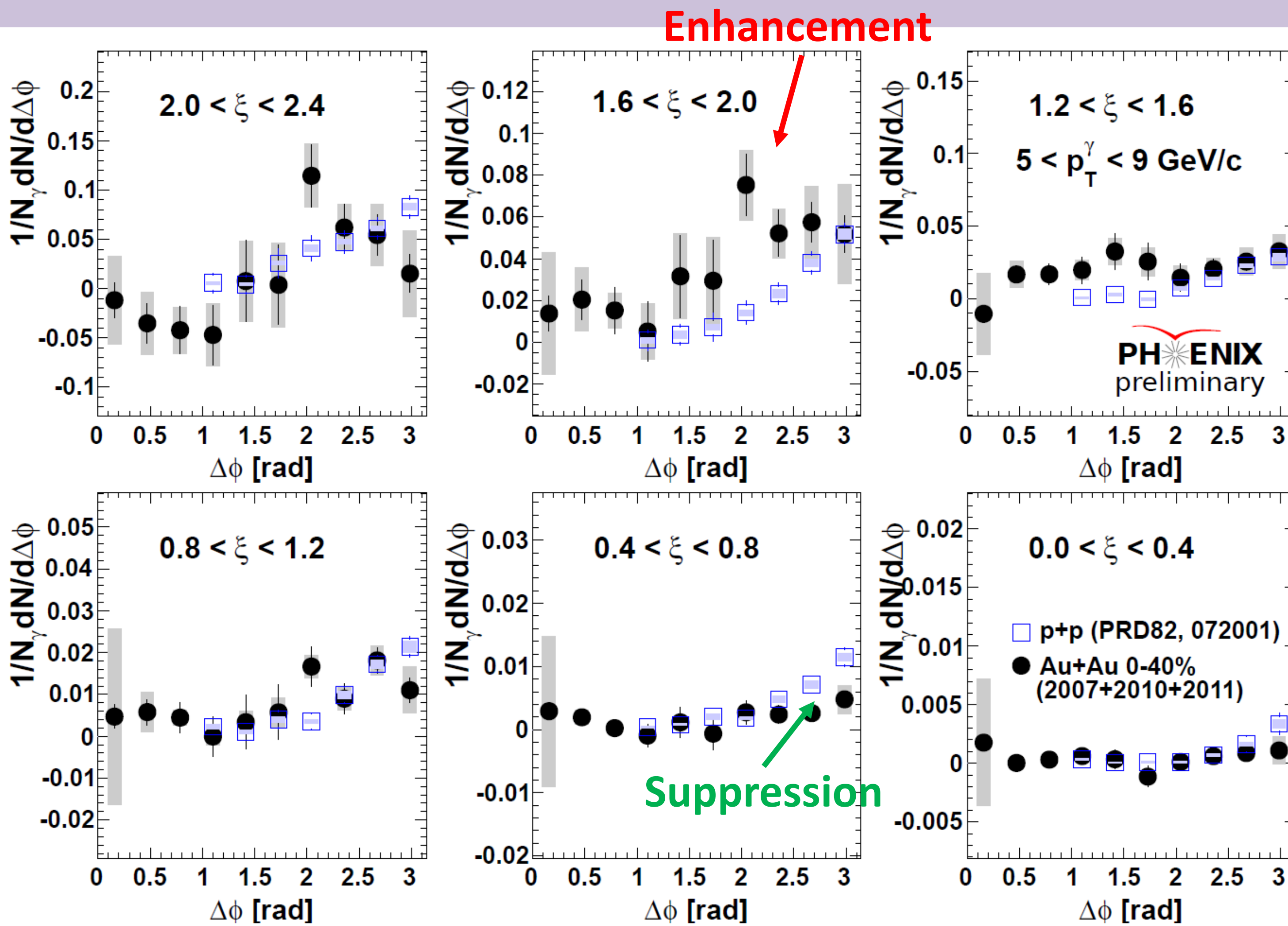
$\xi = \ln(1/z_T)$

$z_T = \frac{p_T^h}{p_T^\gamma}$

- Combine 4.4 billion minimum bias Au+Au data from 2011 to previous measurement (from 2007 and 2010)

p+p points below $\Delta\varphi$ < 1 rad are not shown, due to the photon isolation cut on the near-side.

Measure γ_{dir}-h in Au+Au



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- **Away-side yield modification in Au+Au**

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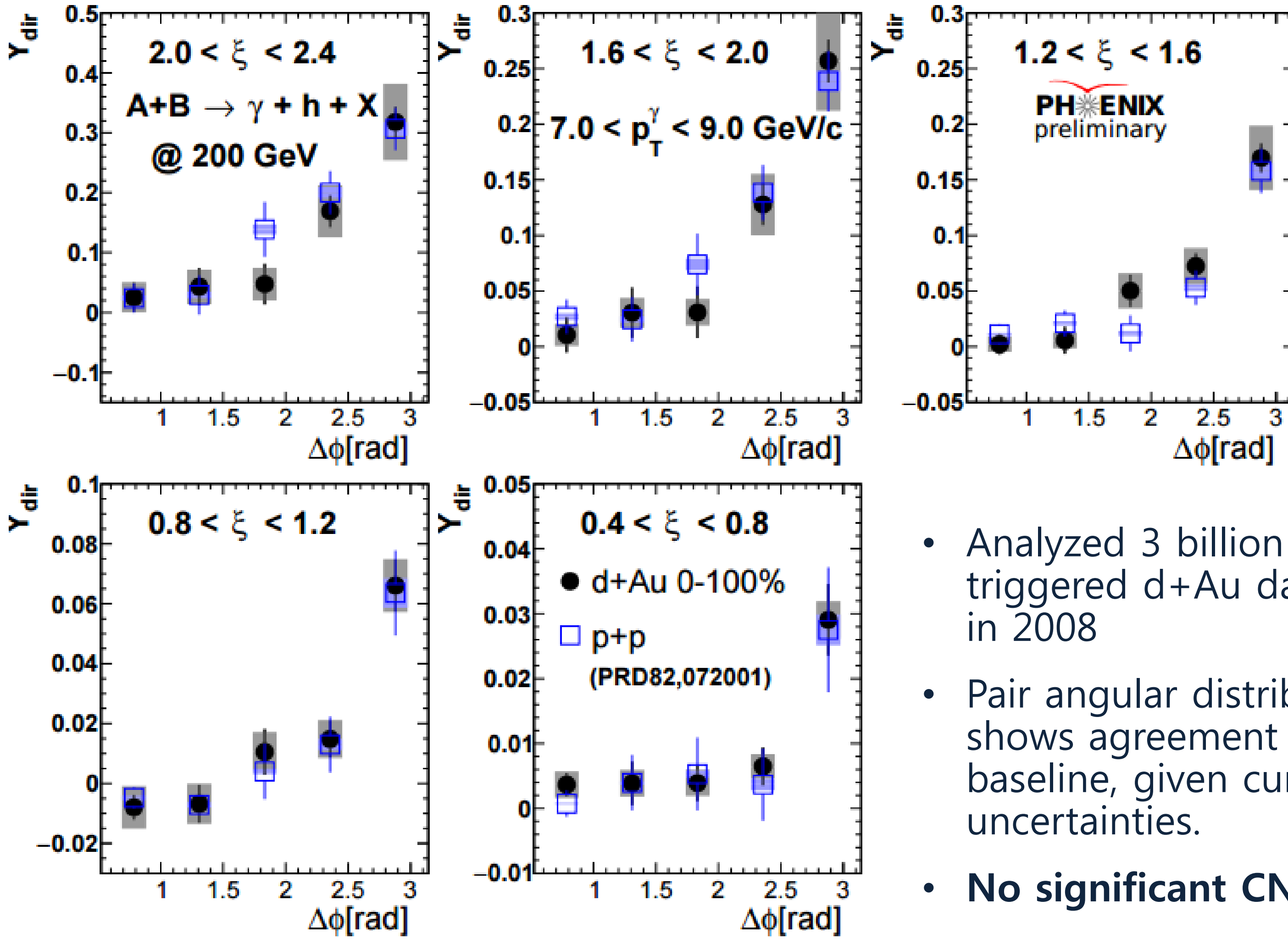
How do things look in d+Au?



$\xi = \ln(1/z_T)$

$$z_T = \frac{p_T^h}{p_T^\gamma}$$

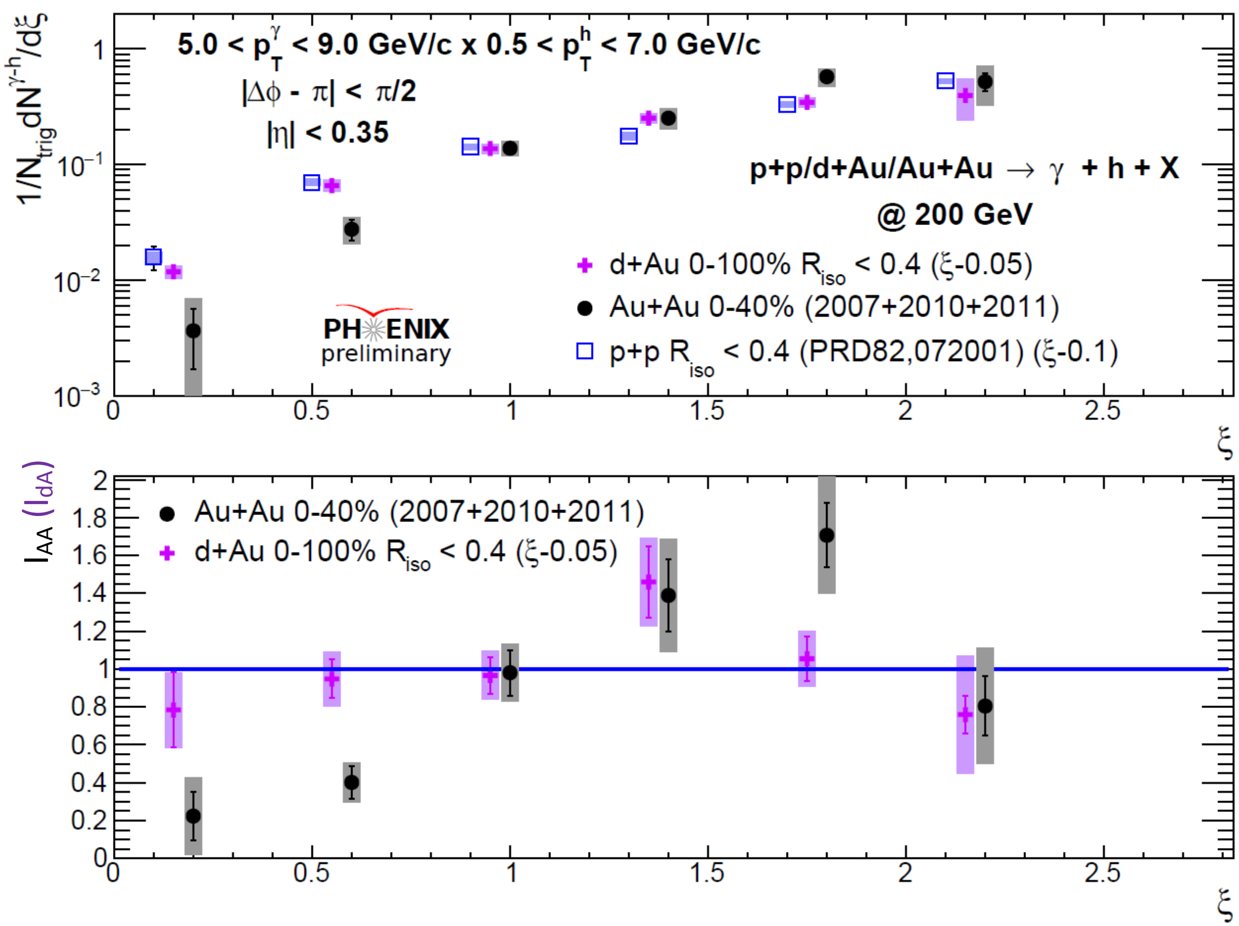
- Analyzed 3 billion high p_T triggered d+Au data taken in 2008
- Pair angular distribution shows agreement with p+p baseline, given current uncertainties.
- **No significant CNM effect**

Measure jet fragmentation function

$$p_T^{\gamma} \approx p_T^{jet} \qquad z_T = \frac{p_T^h}{p_T^{\gamma}} \qquad \Longrightarrow \qquad D_q(z_T) = \frac{1}{N_{evt}} \frac{dN(z_T)}{dz_T}$$

$$\xi = \ln(1/z_T)$$

$$I_{AA} = \frac{Y_{AA}}{Y_{pp}} \sim \frac{D_{AA}(z_T)}{D_{pp}(z_T)}$$



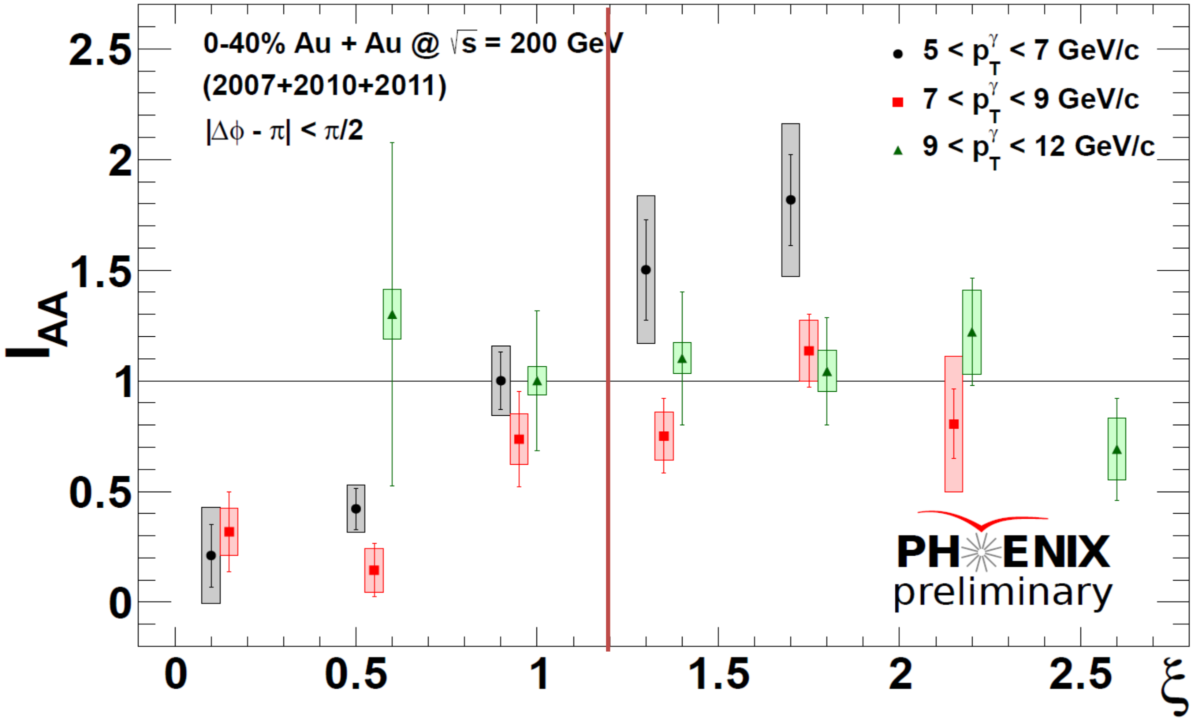
Modification in Au+Au! Suppression in low **ξ** and enhancement in high **ξ**

Transition from suppression to enhancement at **ξ** ~ 1

In d+Au, no significant modification

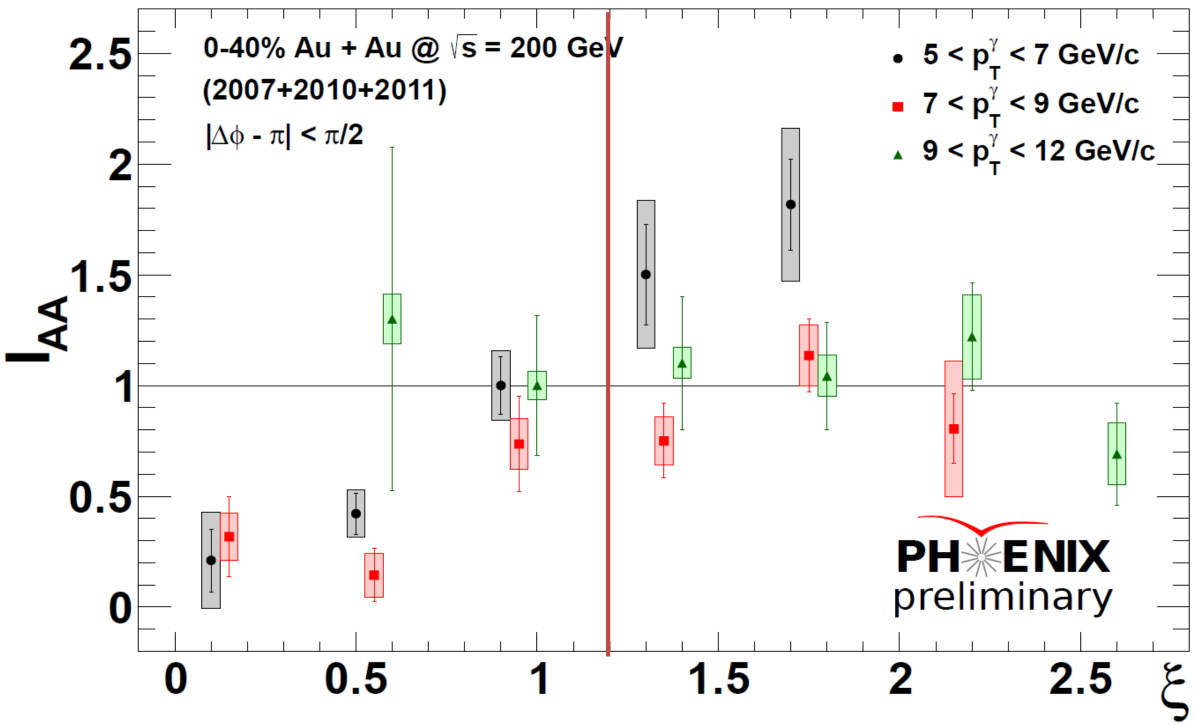
$$I_{dA} = \frac{Y_{dA}}{Y_{pp}}$$

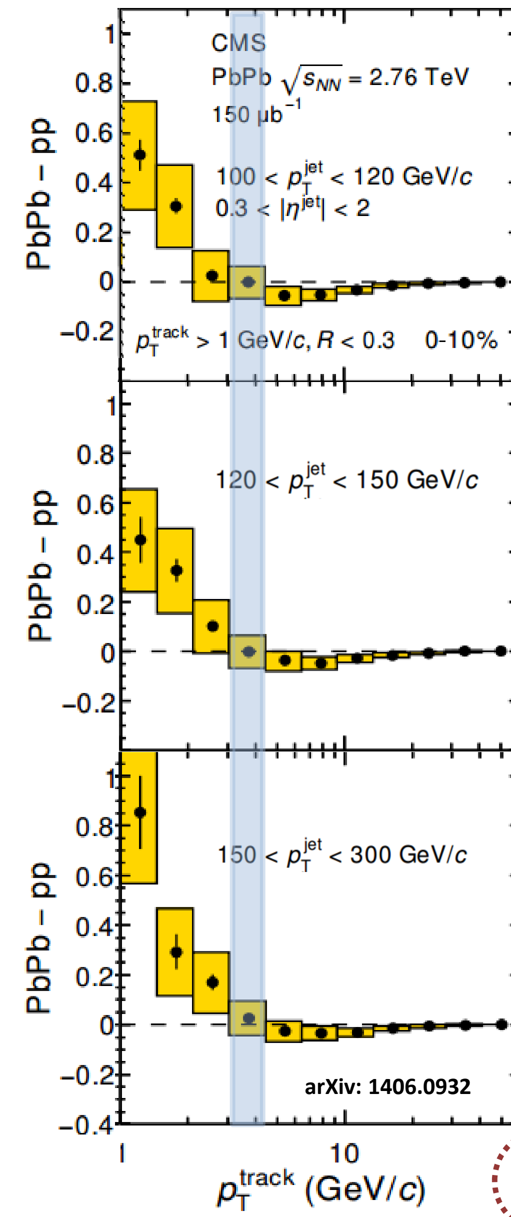
Where does the transition occur?



Transition from suppression to relative enhancement:
ξ ~ 1.2 at RHIC?

Where does the transition occur?

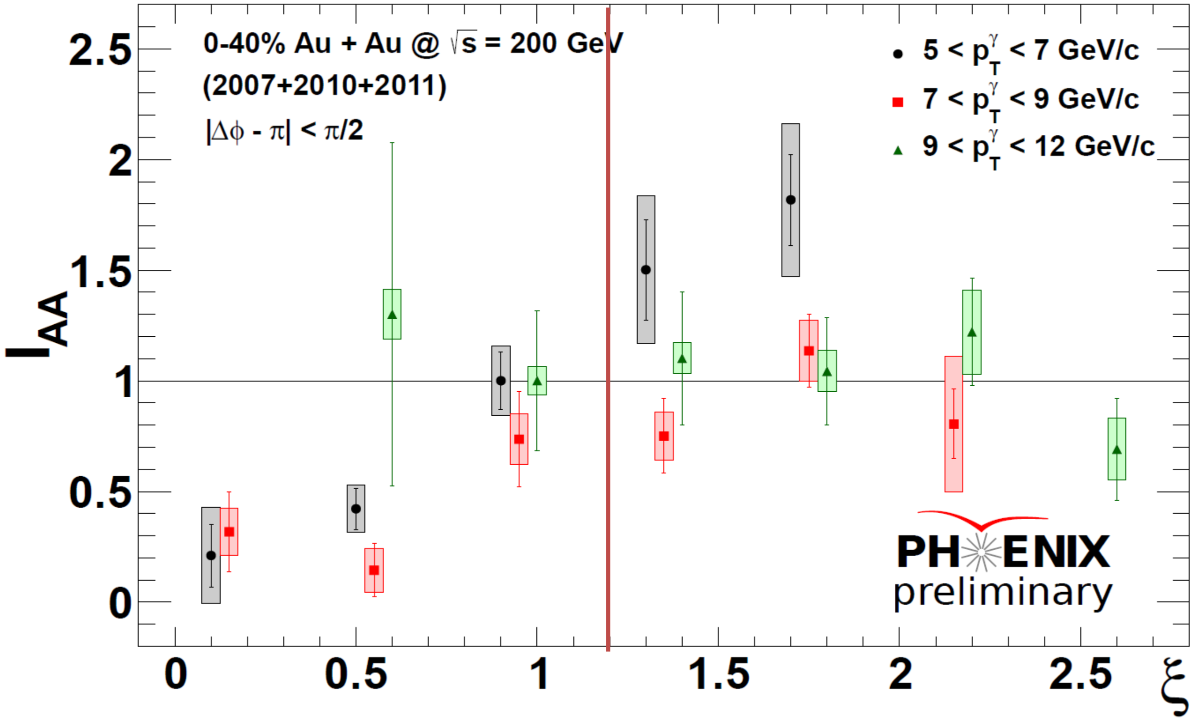


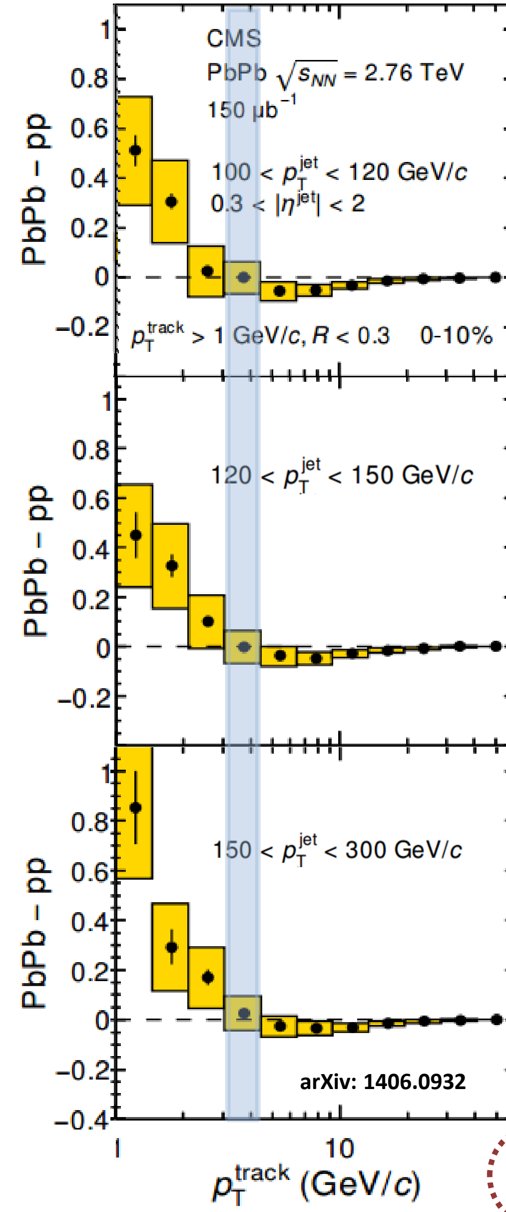


Transition from suppression to relative enhancement:
$p_{T,assoc}$ ~ 3 GeV/c at LHC
$p_{T,assoc}$ = ? at RHIC

Are we seeing a redistribution of energy within the jet or medium response?

Where does the transition occur?





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Fixed ξ or fixed $p_{T,assoc}$?

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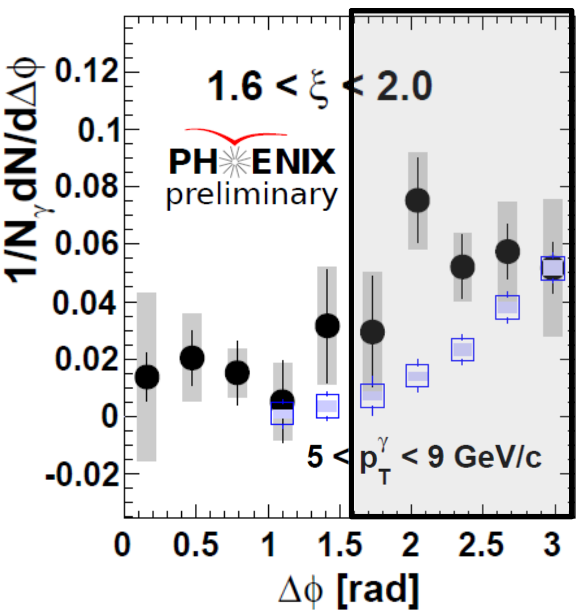
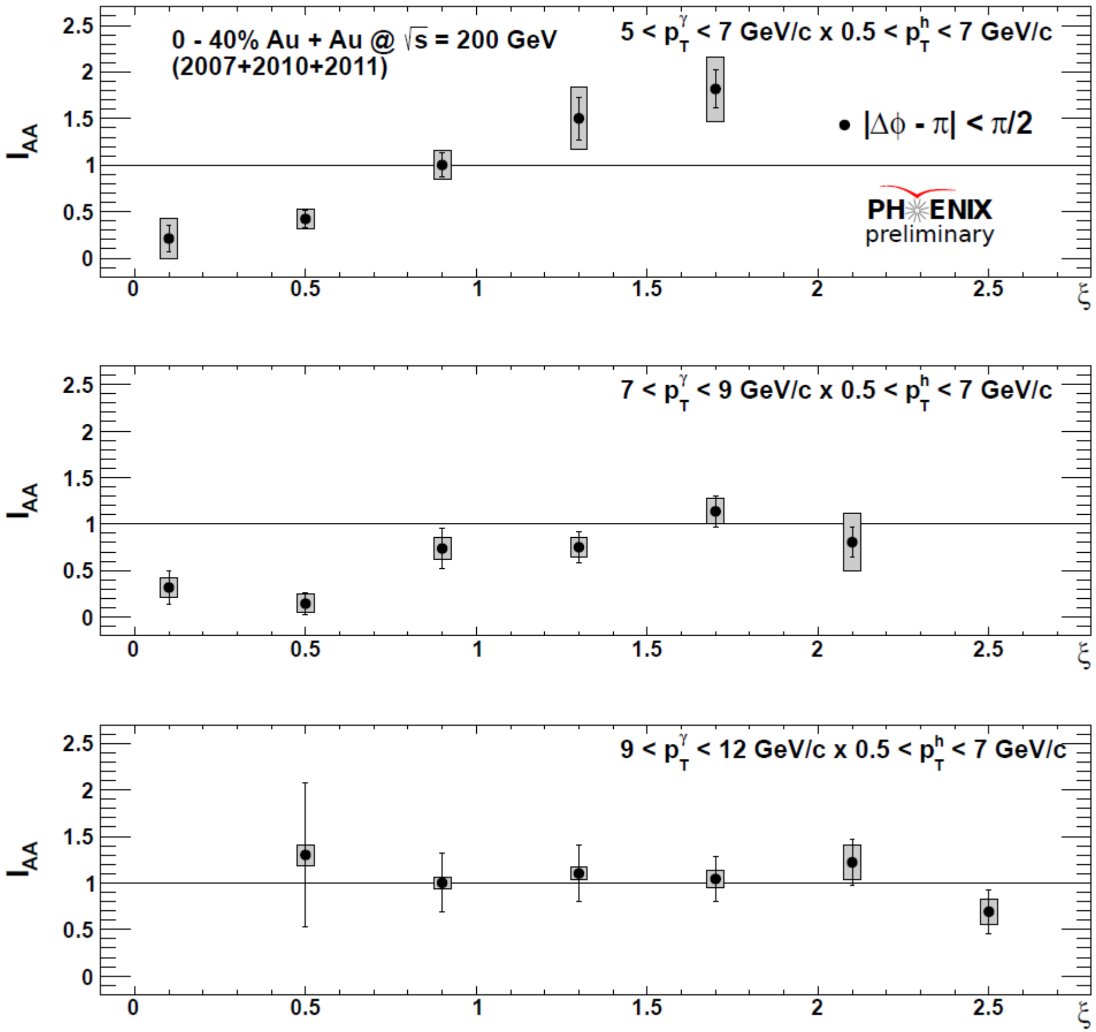
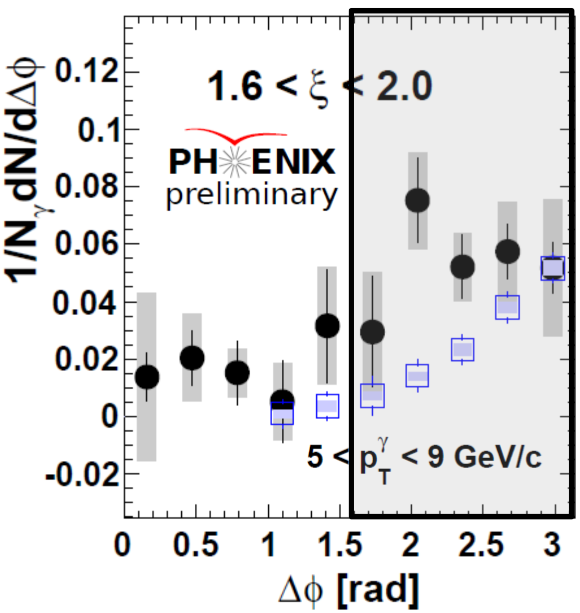


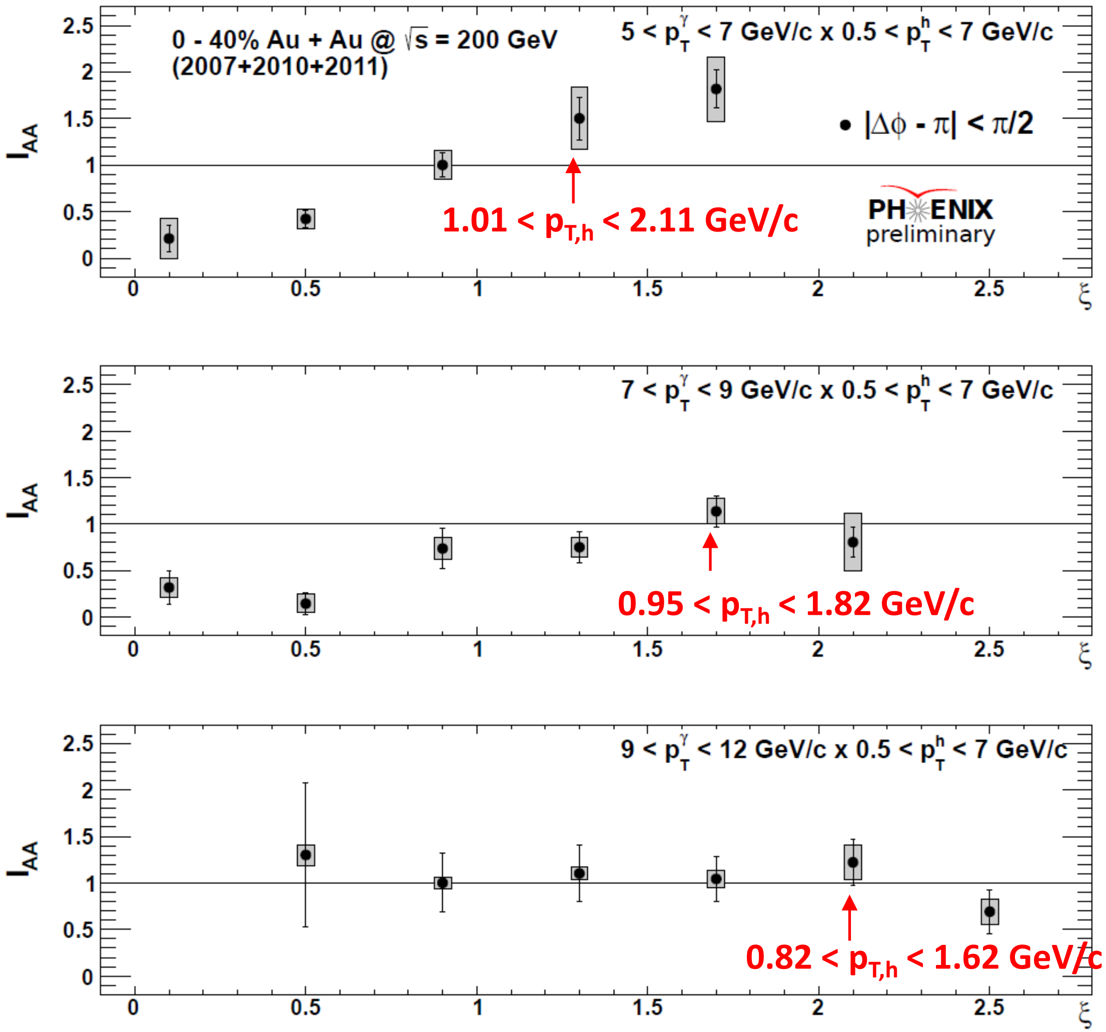


Fixed ξ or fixed $p_{T,assoc}$?

Does not look like fixed ξ

For enhancement vs p+p:
$p_{T,assoc}$ ~ 1-2 GeV/c (?)





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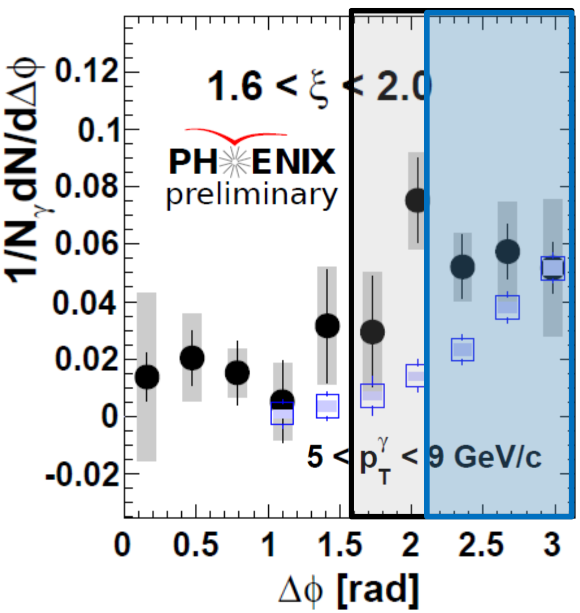

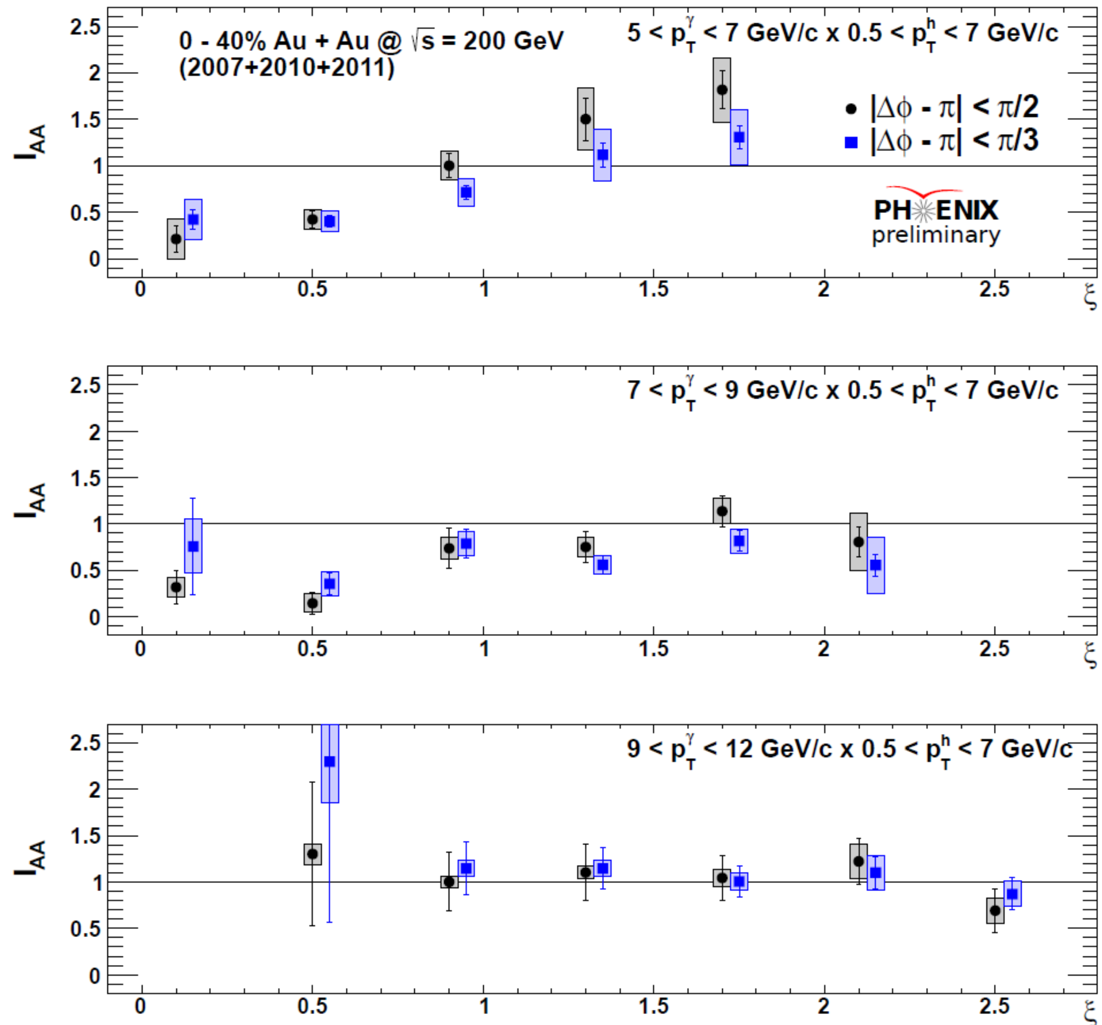

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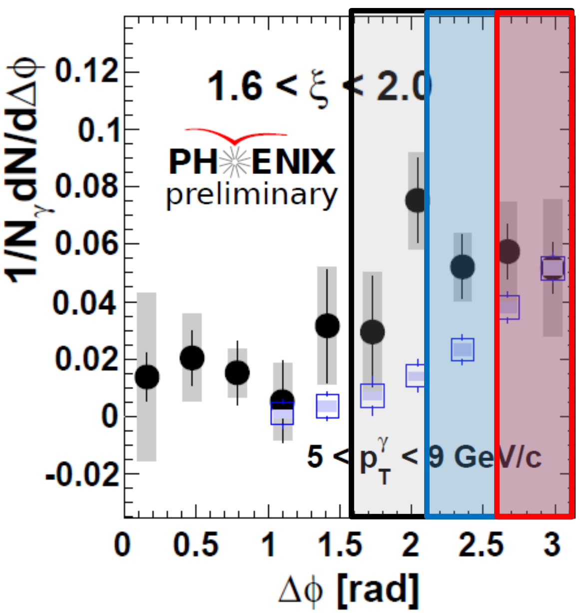
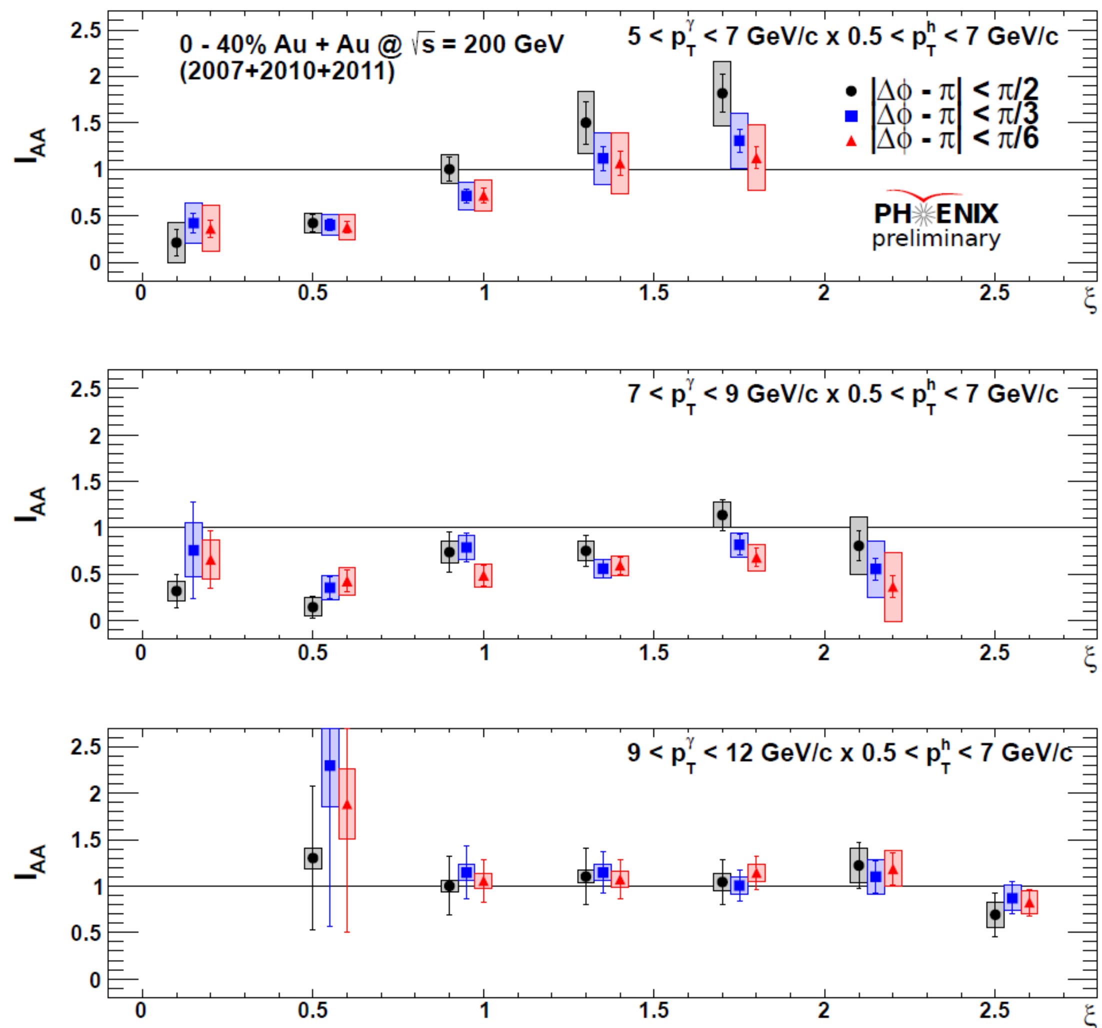


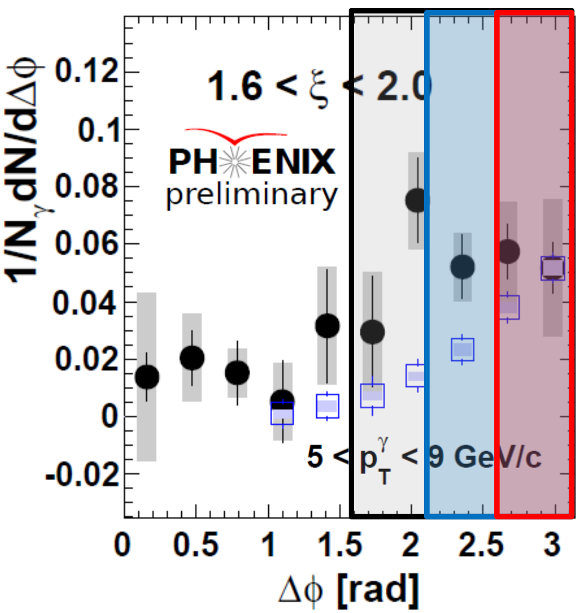


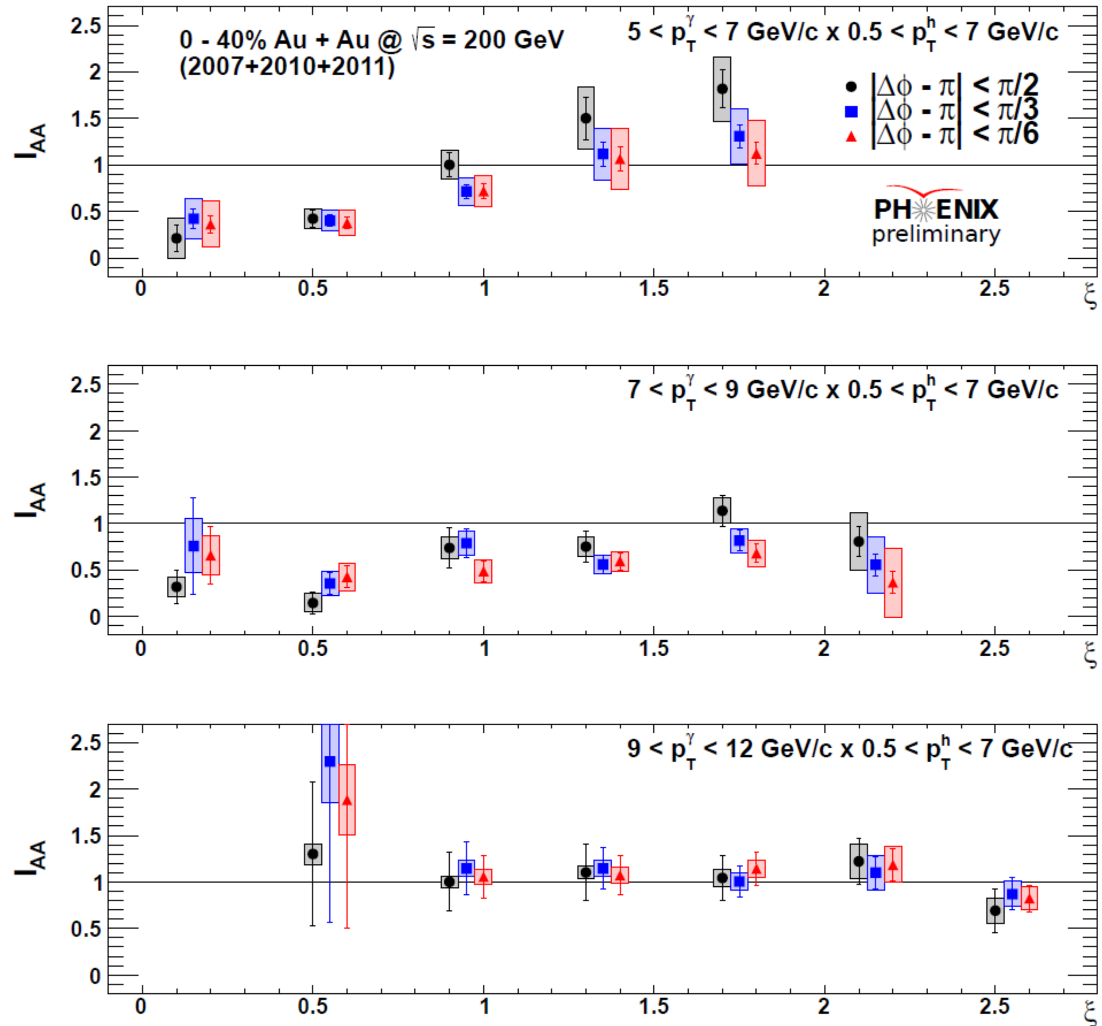
Where does the lost energy go?

Soft particles enhanced at high ξ compared to low ξ

Effect most visible for softest jets and full away-side integration range

Are we seeing the medium response to the jet?



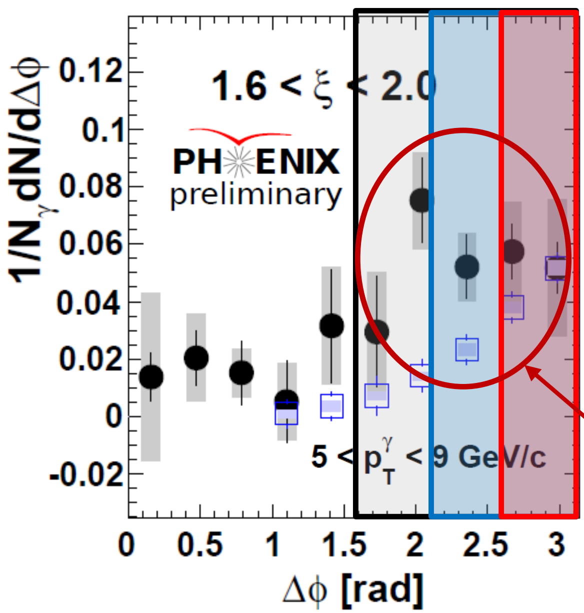


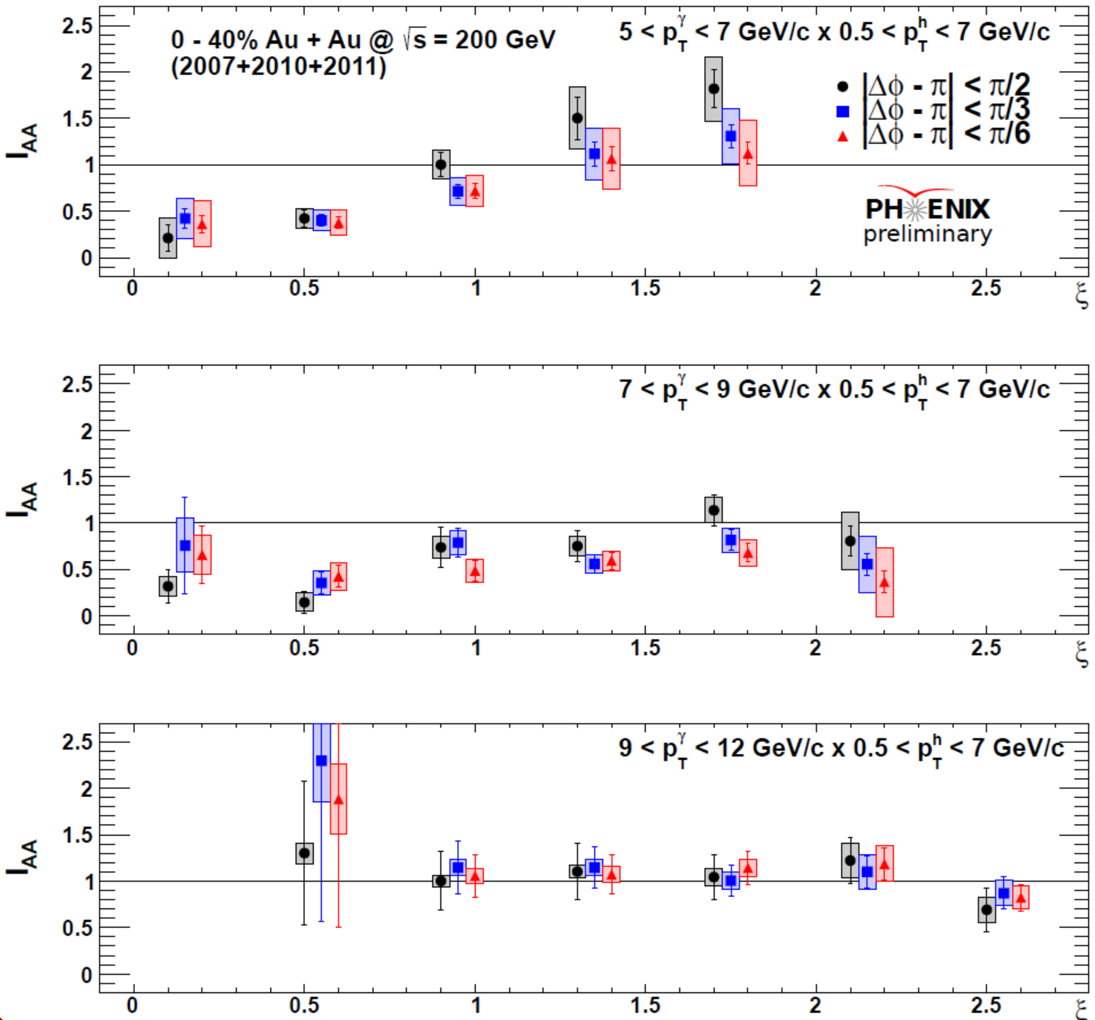
Where does the lost energy go?

Soft particles enhanced at high ξ compared to low ξ

Effect most visible for softest jets and full away-side integration range

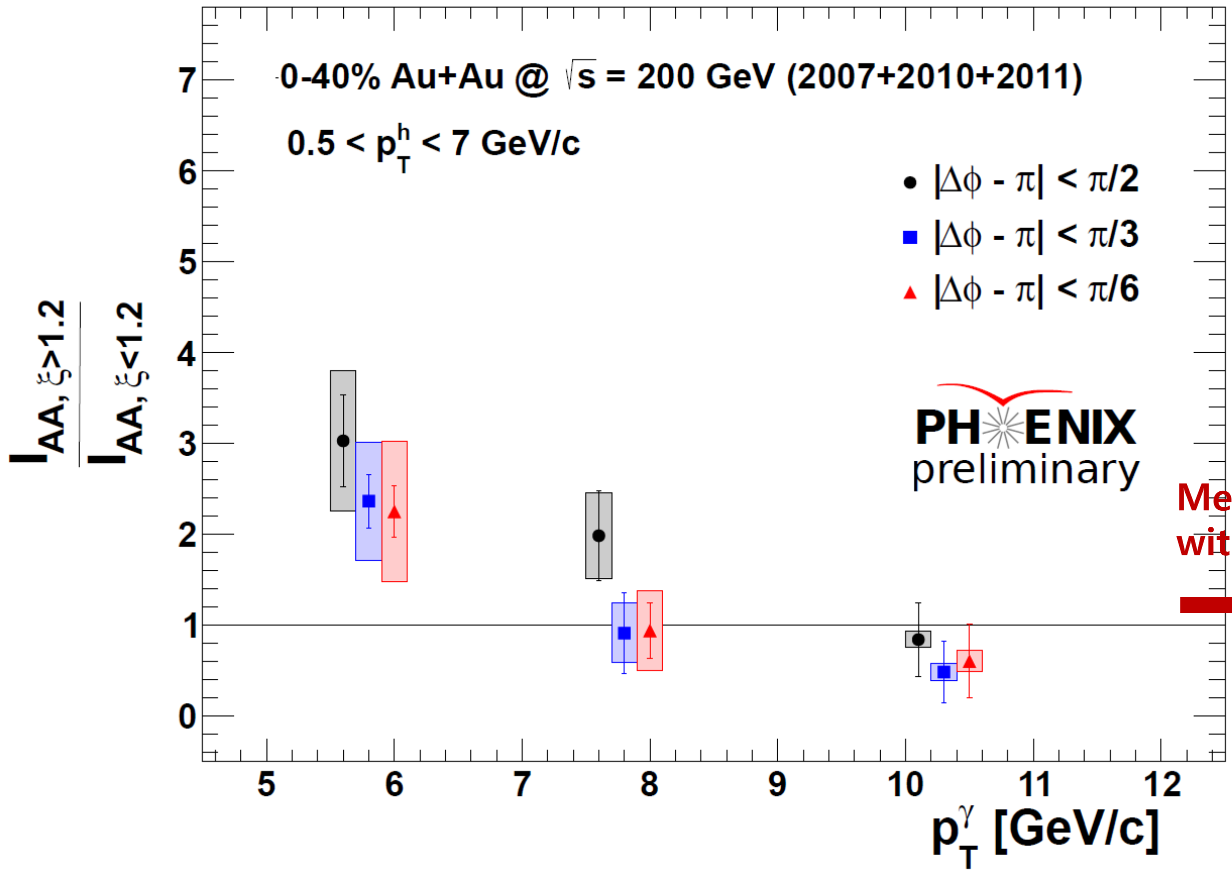
Are we seeing the medium response to the jet?





Particle yields enhanced at larger angle with respect to the away-side jet axis.

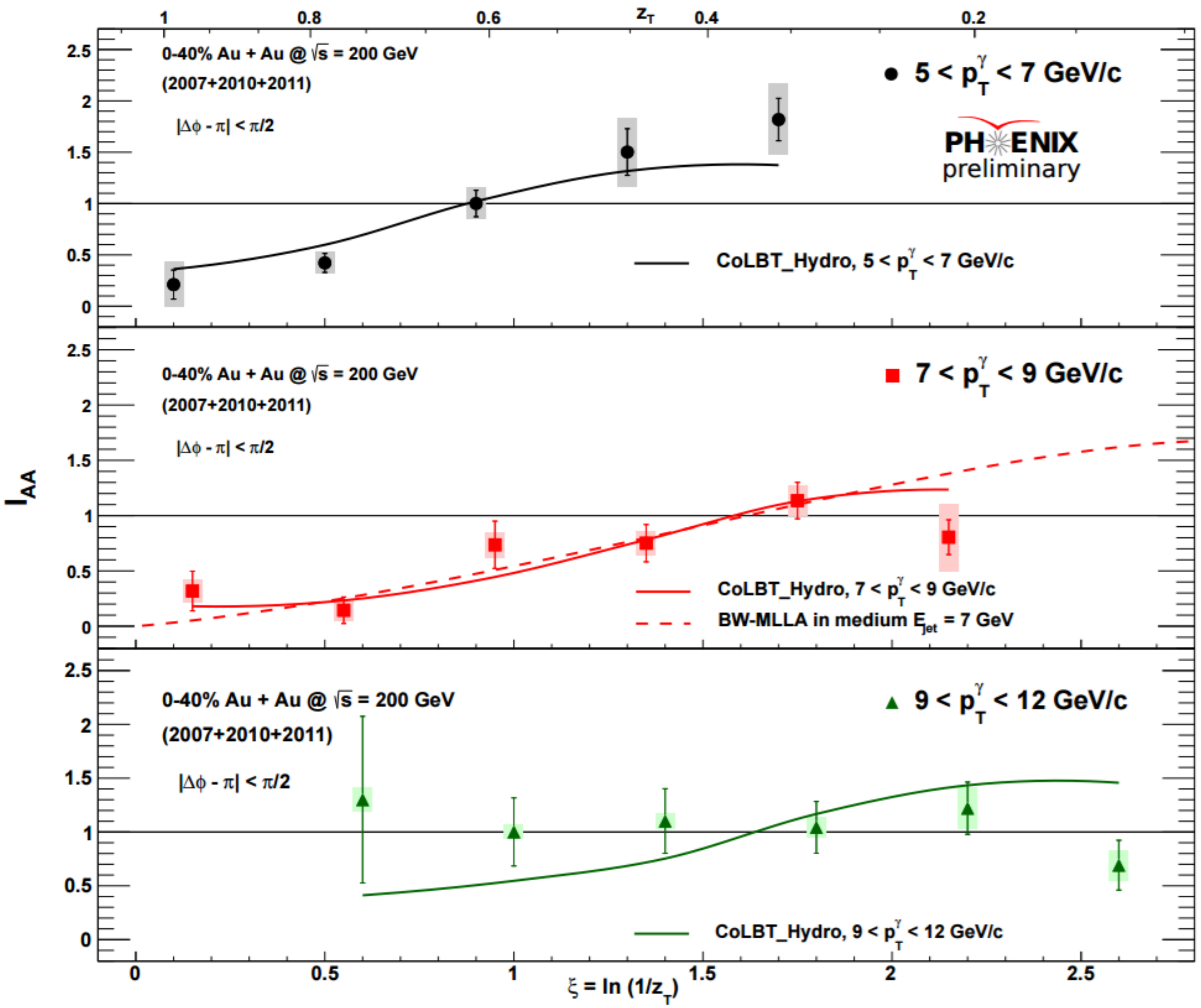
Kinematic dependence of enhancement



Measure harder jets with LHC energy

- ❑ Relative enhancement show p_T dependence
- ❑ <u>Softer jets: more broadened</u> ->particles produced from jet-induced medium excitations?
- ❑ <u>Harder jets: more collimated</u> ->particles more correlated with the jet?
  - – Consistent with observation of minimal jet shape modification at LHC

Comparisons to theory



Transition not at fixed ξ

Linear Boltzmann Transport

- kinetic description of parton propagation
- hydro description of medium evolution
- track thermal recoil partons & their further interactions in medium

Jet transport in medium + jet induced medium excitations

- He, Luo, Wang and Zhu, arXiv: 1503.03313v2 (2015)
- He, Luo, Wang and Zhu, arXiv:1503.0331;

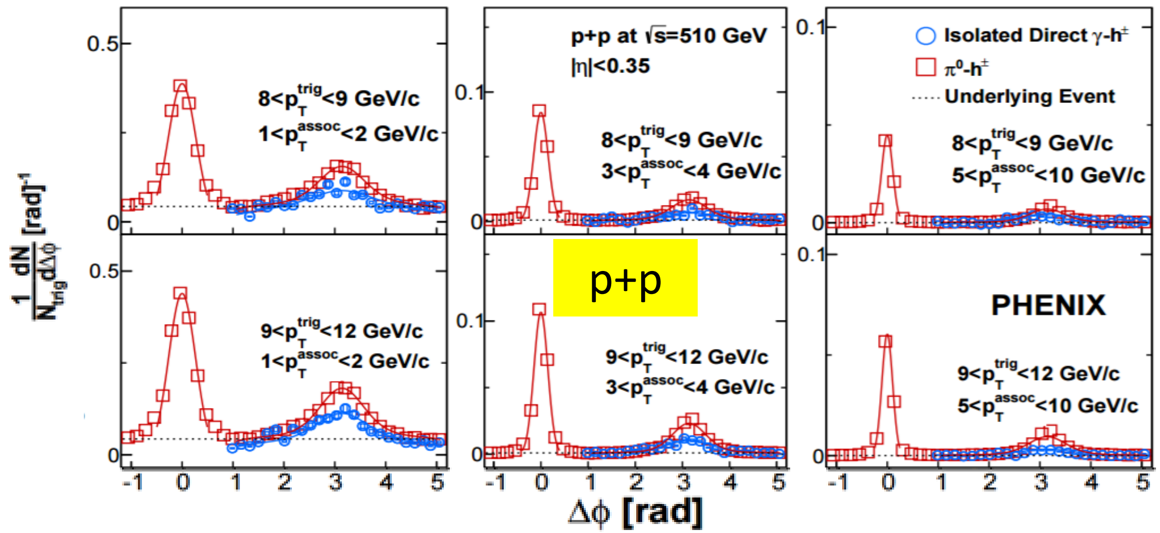
Modified Leading Log Approximation

Modeling the energy loss in the medium as an increased parton splitting probability

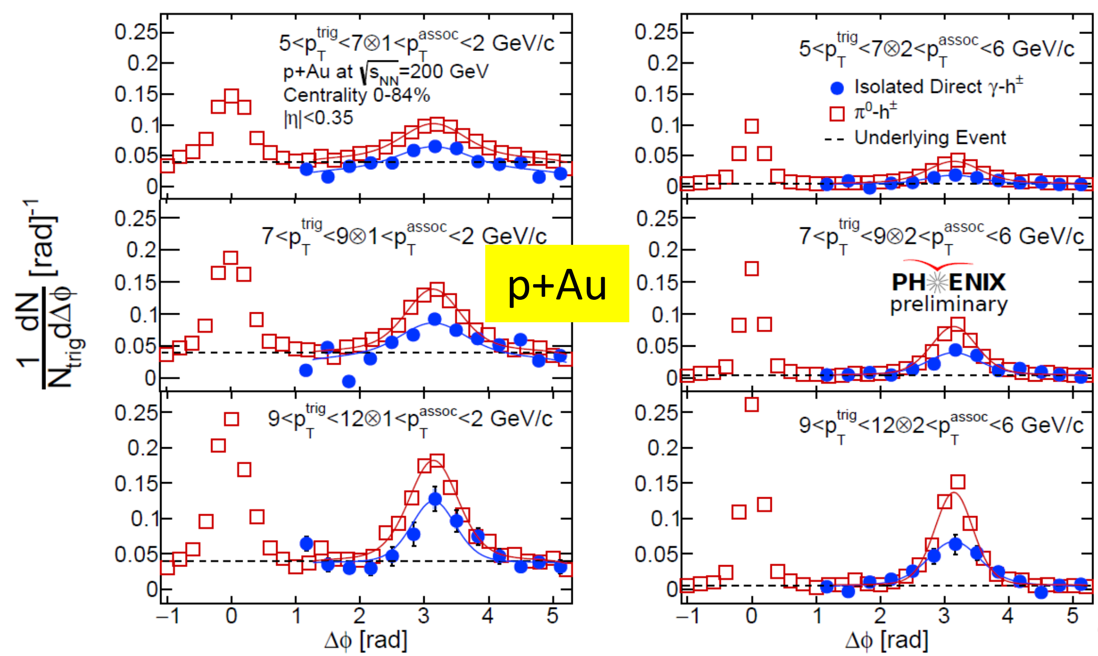
- Borghini and Wiedemann, arXiv: hep-ph/0506218 (2005)

γ_{dir}-h in p+p and p+A

New measurement
- p+p at $\sqrt{s}$ =510 GeV (2013)
- p+Au at $\sqrt{s}$ = 200 GeV (2015)



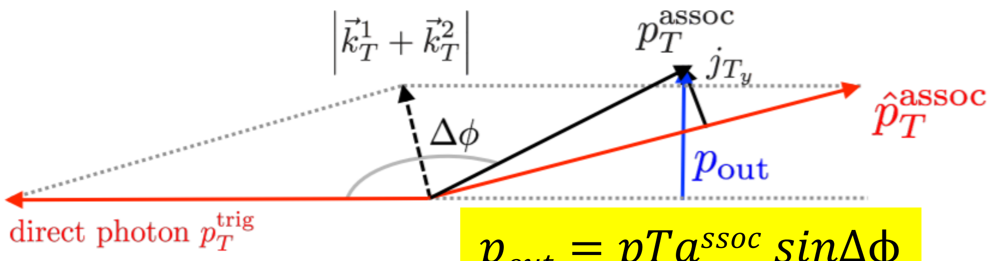
- ❑ π^0-h near-side yields larger than the away-side yields
  → trigger bias



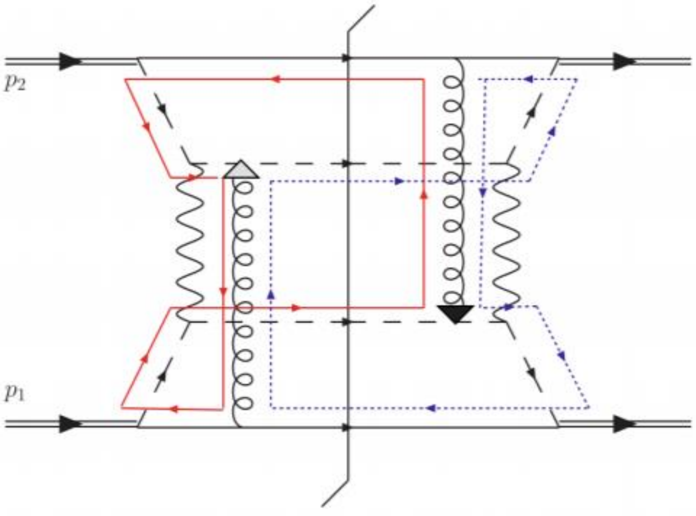
- ❑ For the same p_T^{trig}, larger associated yields observed in π^0-h compared to γ_{dir}-h
  → π^0 triggers sample larger jet energy than direct photons.

γ_{dir}-h points below $\Delta\varphi < 1$ rad are not shown, due to the photon isolation cut on the near-side.

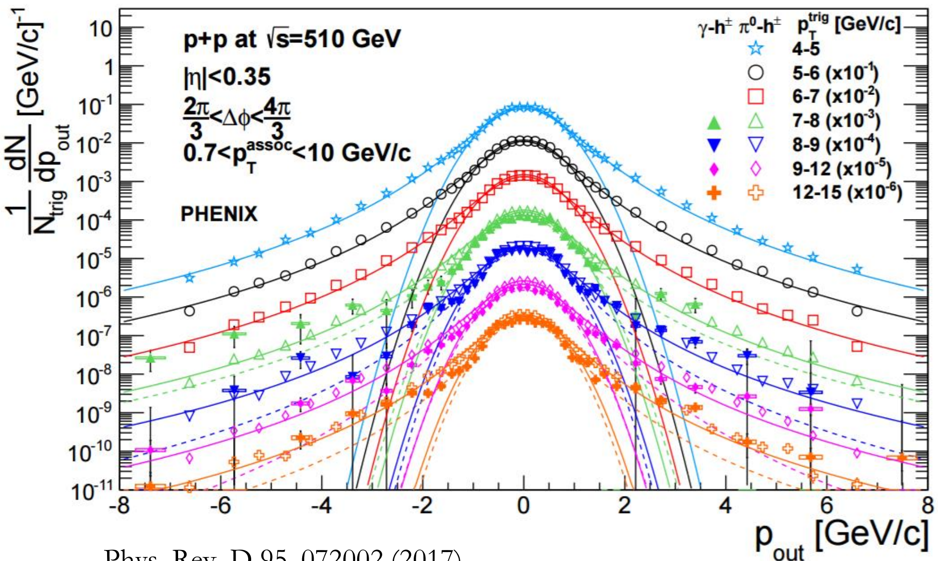
γ_{dir}-h in p+p and p+A



$p_{out} = pTa^{ssoc}\ sin\Delta\phi$



Nearly back-to-back two particle angular correlations give sensitivity to initial- and final-state transverse momentum k_T and j_T



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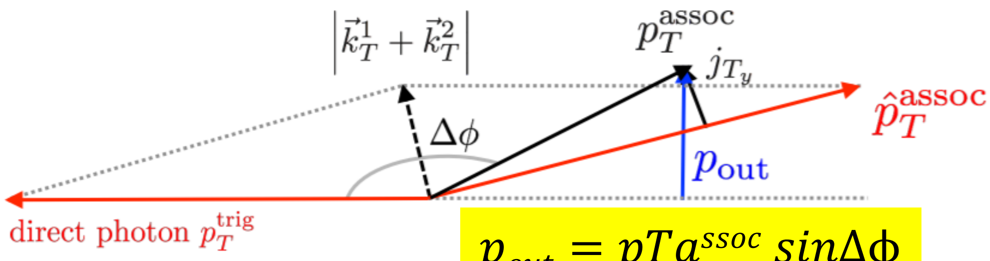
Perturbative transverse-momentum-dependent (TMD) evolution, which comes directly from the generalized TMD QCD factorization theorem, predicts increasing momentum widths with hard scale of interaction.

γ_{dir}-h in p+p and p+A



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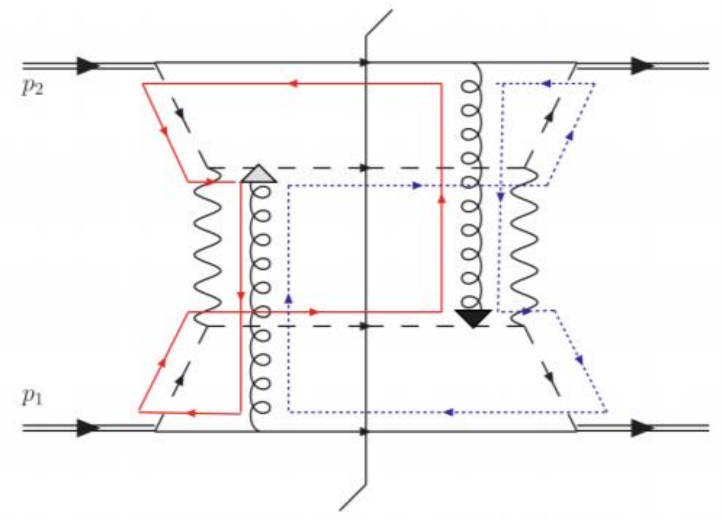

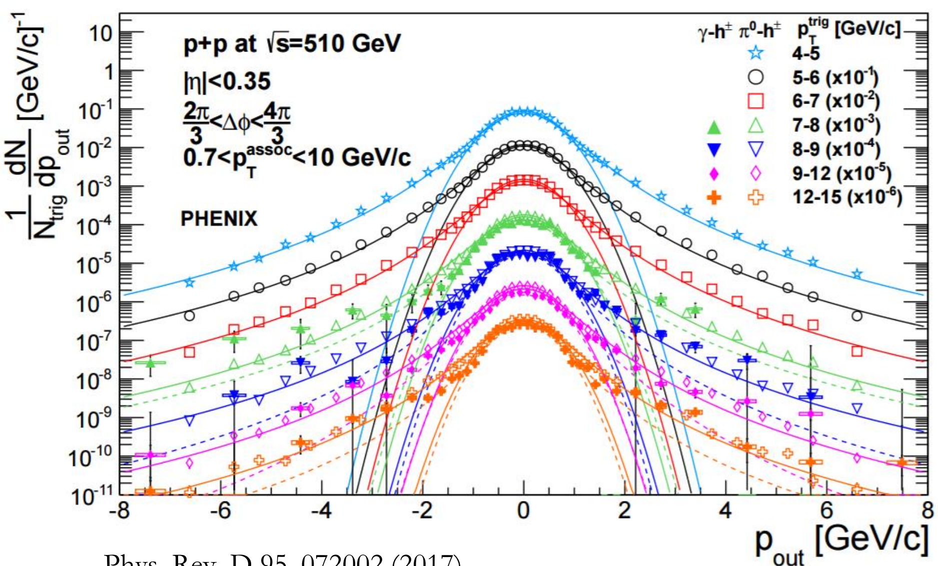

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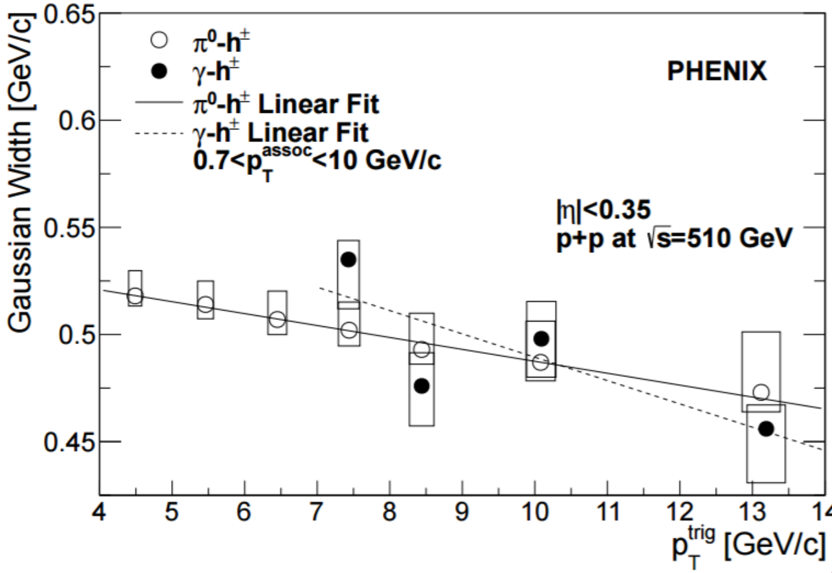
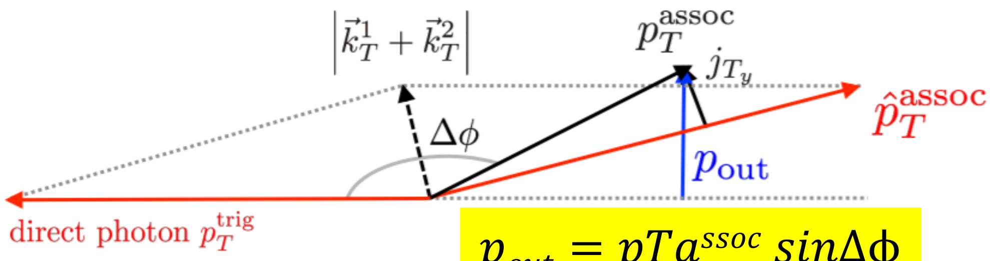


γ_{dir}-h in p+p and p+A



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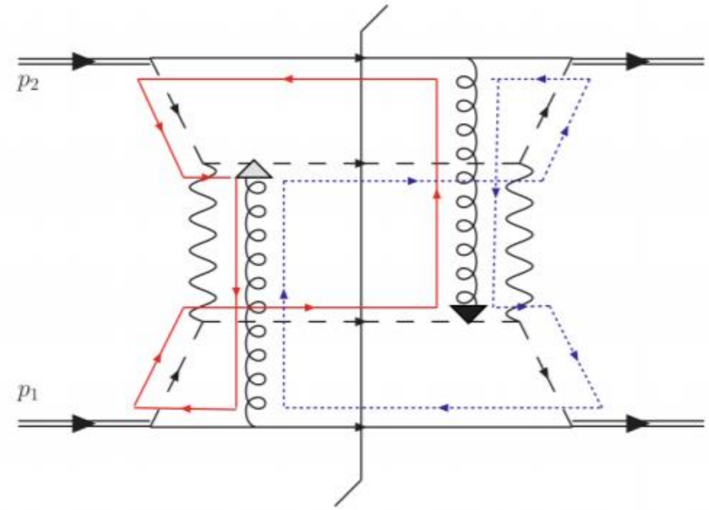
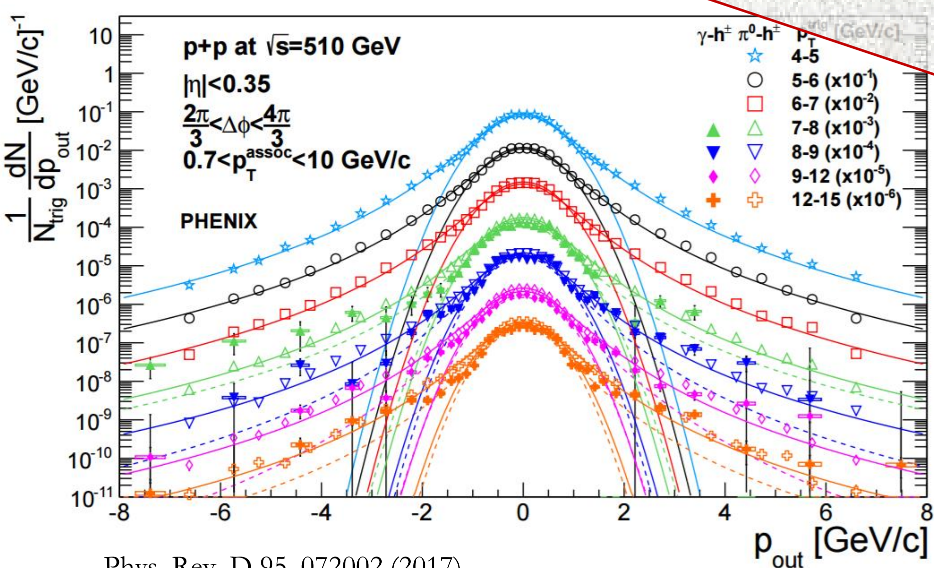
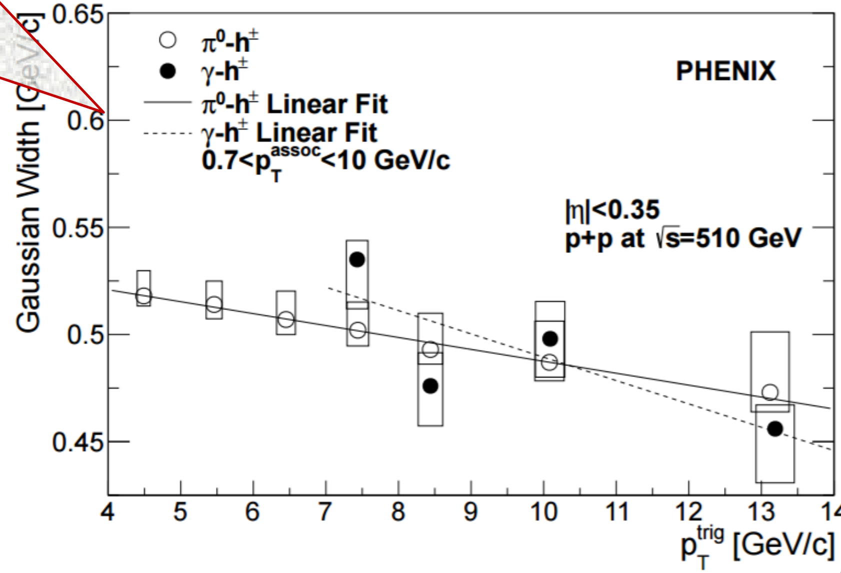


- p_{out} nonperturbative momentum widths vs p_{trig}
  - decreasing widths observed as p_T^{trig} increases
  - factorization breaking?





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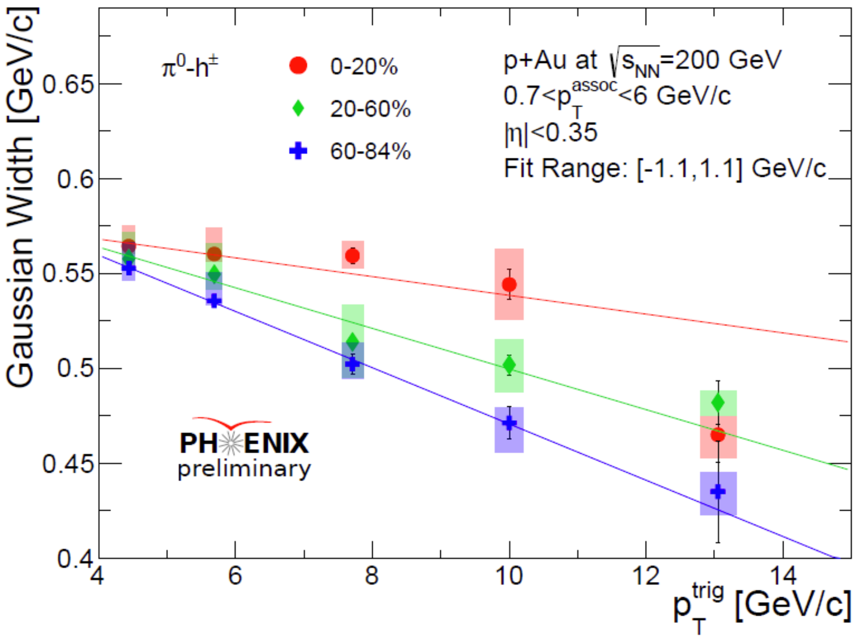
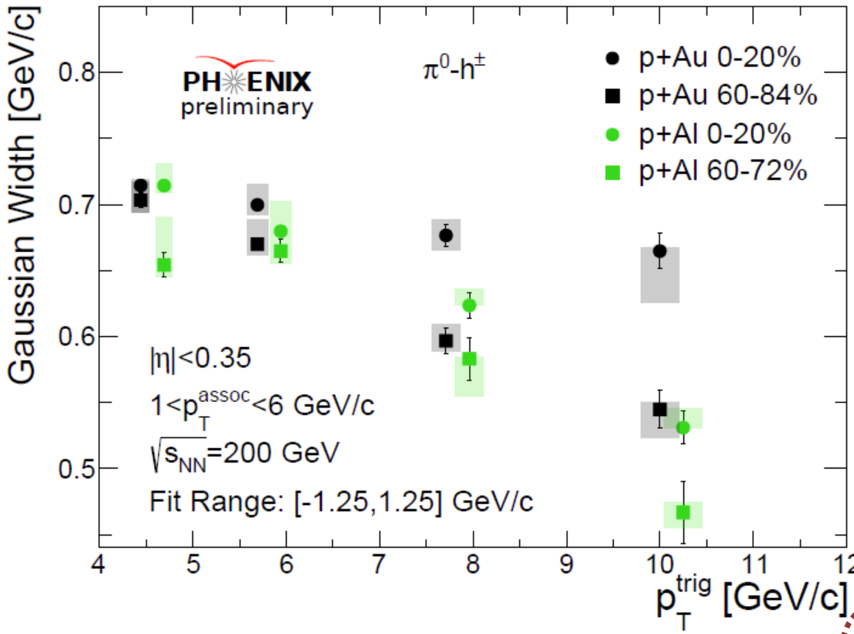
Explore centrality dependence in p+A

- In p+Au collisions, centrality dependence of the Gaussian widths as a function of p_T^{trig} in π^0-h measurement is observed.
- Centrality dependence is also present in p+Al collisions - not as strong as in p+Au.
- Effects from k_T broadening? Multiple scattering?





Summary

- Modification to effective fragmentation function is observed in Au+Au collisions using γ_{direct}-h correlation measurement.
- Variation of away-side integration range suggests low p_T jet broadening in addition to enhancement at low $p_{T,h}$.
- Results from higher statistics in Au+Au hint that the away-side jet modification is due to medium response.
- In d+Au collisions, no significant modification to yield is observed, suggesting minimal CNM effect.
- p+p collisions at 510 GeV – effects due to factorization breaking of nonperturbative functions?
- π^0-h correlations in p+A collisions show centrality dependence of the nonperturbative widths. Interpretations ongoing!

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Thank you!